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25 February, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The following Papers were submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Authors.

Paper No. 5041.

"St. Germans Sluice and Pumping-Station."

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Historical.

The drainage and protection of large areas, originally reclaimed from tidal influence, has occupied the attention of engineers for many years. The Middle Level, which is a typical example, covers an area of 174,000 acres, the major portion being agricultural land situated in the heart of the Cambridgeshire Fens; this was originally a part of the Bedford Level. The area is bounded on the north-east and south-west sides by barrier banks, about 20 and 14 miles in length respectively, which protect it from the flood-waters of the tidal sections of the Ouse and Nene.

For nearly 300 years the difficulty of adequately discharging the flood-waters of the Middle Level has been apparent, and its history has been centred around this problem. The area is virtually land-

locked and separated from the tidal Ouse by 6 miles of marshland, at an average level of 10 feet above the fenland. The constant settlement of the fenland due to drainage is largely responsible for the difficulties met with in maintaining the drainage of the area, and the efforts made at the Middle Level have been concentrated on lowering the water-levels and drains to keep pace with the shrinkage. The average rate of shrinkage is now about ½ inch a year.

The south-western boundary consists of a range of hills rising to 150 O.D., while to the north-east several miles of marshland lie between the Middle Level area and the Wash, into which the flood-waters from the area eventually find their way. The fenland is in many places as low as — 4 O.D. The high-water spring-tide levels at the outfall-sluice vary from 13 to 17 O.D. and the L.W.O.S.T. level at peak flood-periods is about O.D. The bulk of the rain and snow which falls into the Middle Level area has to be pumped into high-level drains in order to discharge into the sea. For this purpose the area is intersected by 150 miles of main waterways, principally artificial, and subdivided into about 50 minor internal drainage districts, varying from 400 to 15,000 acres. Each district possesses one or more pumps pumping water into the Middle Level high-level drains and waterways, whence it is eventually discharged at low tide by gravitation into the river Ouse.

The problem of fen-drainage is twofold; firstly, to protect the area from inundation from the tidal and flood-waters of the adjacent Ouse and Nene and secondly, to keep the surplus water which falls in the form of rain or snow in the area from rising above fen-level, thus causing floods and damage.

When Vermuyden prepared his scheme for reclaiming and draining the Fens, it is doubtful if he anticipated the shrinkage of the surface-level. His pioneer undertaking consisted principally of providing straight cuts to by-pass the natural river and constructing long embankments, designed to keep out the tidal- and flood-waters from the Fens. For this purpose he constructed barrier-banks, as well as several new cuts and waterways to conduct the flood-waters from the highlands to the outfall in times of flood. The Middle Level in early days drained through Wisbech into the river Nene, but in course of time, owing to the shrinkage of the land, it was found necessary to divert the outfall from the river Nene to the river Ouse, through Salters Lode and Tong's Drain, in order to obtain effective drainage.

Eventually this again proved to be unsatisfactory, due to further shrinkage, and in 1840 the Middle Level Commissioners, acting on a report by Messrs. Burges and Walker, MM. Inst. C.E., decided to adopt a scheme whereby the outfall was transferred to St. Germans

on the Ouse, a distance of about 8 miles downstream from Tong's Drain, at an estimated cost of £450,000. This scheme consisted of cutting a new Main Drain through 12 miles of marshland and erecting a sluice at its confluence with the Ouse at St. Germans.

By this scheme reduced low-water tidal levels were obtained. The new Main Drain from St. Germans to Upwell passed under the old Drainage river at Well creek. For some years the new outfall at St. Germans proved satisfactory. Unfortunately, in May 1862, the sluices at St. Germans failed, admitting water from the tidal river Ouse into the Main Drain. The subsequent scouring action of the tidal water eventually burst the containing Main Drain bank and about 6,000 acres of land were inundated. The Middle Level Commissioners called in the late Sir John Hawkshaw, Past-President Inst. C.E., who was given a free hand to do what he thought necessary to shut out the tidal waters. After considerable difficulty he constructed a dam across the Main Drain about ½ mile above the St. Germans sluice, and excluded the tide. The construction of the dam took about 6 weeks. A Paper by Sir John Hawkshaw, describing the construction of this dam, was read before The Institution in 1862.[1] At the time it was realized that the Hawkshaw dam was a remarkable work, and when it became necessary to remove the dam and siphons for the new pumping-station and sluices, hereinafter described, the ingenious and robust construction of the dam, siphons and valves was revealed.

The Hawkshaw dam kept back the tidal water, and the evacuation of the internal flood-water was temporarily effected through adjoining drainage districts. Sir John Hawkshaw then recommended the Middle Level Commissioners to erect a battery of sixteen siphons over the dam, each 3 feet in diameter. This recommendation was adopted and carried out in order to restore the drainage of the area. After a few years' trial the siphons did not prove satisfactory, principally owing to the silting-up of the delivery ends during the summer months, when the backwater supplies were at a minimum.

Sir John Hawkshaw at a later period suggested that the Middle Level Commissioners should put down further siphons, or, alternatively, should erect an entirely new sluice on a diversion of the Main Drain (Fig. 1, Plate 1). The scheme for the new sluice was adopted in preference to further siphons and was completed in 1880. The cost of the disaster in 1862, and of the subsequent siphons and new sluices, was £250,000.

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1 "Account of the Cofferdam, the Syphons, and other works, constructed in consequence of the failure of the St. Germains' Sluice of the Middle Level Drainage," Minutes of Proceedings Inst. C.E., vol. xxii. (1862–63), p. 497.

These sluices had three sluiceways or openings, each 17 feet wide and fitted with clap or pointing doors, which worked automatically with the fall and rise of the tide. Each pair of doors gave an effective opening width of 13 feet 4 inches. For several years these sluices effectively drained the area. However, during the 1912 flood it was noticed that the tidal waters in the Ouse did not recede so low as in 1880, due in a large measure to the neglected state of the estuary of the Ouse. Also, the fenland in the area farthest from the sluice, in fact some 30 miles away, was still shrinking. These factors caused a curtailment of the discharge and a loss of hydraulic gradient. It is also interesting to note that during this period the old drainage scoop-wheels, driven by windmills and used by the internal districts, were being gradually replaced by modern centrifugal pumps, connected to either steam- or oil-engines. These modern plants were more efficient, were independent of wind and were more positive in action. The combination of these three factors had seriously affected the drainage-system of the Middle Level.

Dredging operations were taken in hand to improve the waterways, but the subsequent floods of 1916, 1926 and 1928 left no doubt in the minds of the Middle Level Board that their position in times of heavy flood was becoming increasingly serious, inasmuch as the discharge per tide at St. Germans was insufficient. Further, in drought periods the sluices at St. Germans silted up on the tidal side. In 1923 the mud and silt on the tidal side of the sluice had accumulated to a depth of 13 feet above the sill-level, corresponding to 3 feet above water-level on the fen side of the outfall-sluice.

The Author, as Engineer to the Middle Level Commissioners, recommended the Board in 1923 to remove their timber pointing doors and to replace them with steel half-tide Stoney sluices, so that the mud and silt could be scoured away. It was thought that these sluices would have a beneficial effect, as the water could be held up until the tide had receded and could be used more effectively, whereas with the ordinary clap or pointing doors the water on the fen side merely discharged as the tide fell, without any scouring action.

During 1924–25 three Stoney sluices, each 17 feet wide, were put in and were, for a time, effective, but the backwater supplies during the dry summer periods proved insufficient. The position of the Middle Level in heavy flood was still unsatisfactory and, in 1929, after discussion the Board decided to adopt a scheme to effect better drainage put forward by the Author.

The Author's scheme for the future discharge of flood-waters was that the Middle Level should erect a larger sluice, supplemented with

pumping-machinery for use in times of flood. A larger sluice only was insufficient for the future needs of the Middle Level. The object of the scheme was to evacuate the surplus water by gravitation through the sluices in normal times, and to use the pumps to lower the water in the Middle Level system in anticipation of flood and during flood, thus providing reservoir-capacity in the 125 miles of internal drains. At the same time, it would be possible to control the water-level in the winter, which was impossible with the gravitation sluices owing to the increasingly high level of low-water tides ; the latter was due to upland flood-waters overriding the tidal water in the river Ouse, together with the ill-conditioned state of the estuary.

In 1928 negotiations were opened with the Land Drainage Branch of the Ministry of Agriculture and Fisheries. After examining the scheme the Ministry recommended it for a grant to the Unemployment Grants Committee, who made a grant of 75 per cent. of the loan and interest for the first 15 years and 37½ per cent. for the remaining 15 years, on a 30-year loan basis. At the same time they stipulated that 75 per cent. of the labour required must come from the distressed areas, and that all materials used should be of British manufacture.

Sluices and Pumping-Plant.

The new outfall-sluice is provided with two sluiceways each 35 feet wide, thus increasing the sluicing width by about 50 per cent. as compared with the sluices erected in 1880. The new sluices are separated by a central pier 7 feet thick (Figs. 2, Plate 1).

Efforts were made to obtain a supply of electricity from the "grid" for operating the pumps, but eventually oil-engines were chosen, as the terms for electric supply were unattractive, due principally to the low load-factor.

The tender for the pumping-plant submitted by Messrs. The Premier Gas Engine Company, of Sandiacre, was accepted; they, as main contractors, supplied three complete pumping-units. Each unit comprised an oil-engine of the horizontal eight-cylinder horizontally-opposed type, of 1,000 B.HP., coupled through David Brown double-helical reduction gear-boxes to Gwynne centrifugal pumps, each 8 feet 6 inches in diameter, with Glenfield & Kennedy sluice-valves. The tender also included auxiliary plant in duplicate, each set driven by two Crossley-Premier 44 B.HP. oil-engines, dynamos for generating electric current for lighting and for operating the main sluices, sluice-valves, house-drainage pumps, exhausters, compressors, fuel-oil tanks and heating-equipment.

The engines and pumps are housed in the abutments of the new sluices, Nos. 1 and 2 units in the north engine-house and No. 3 unit in the south engine-house. Provision has been made in the south engine-house for a fourth unit, the suction and delivery pipes for No. 4 unit being concreted in position and closed off with blank flanges (Fig. 3, Plate 1). The north and south engine-houses are connected by a reinforced-concrete duct, 7 feet wide by 3 feet 6 inches deep at coping-level, across the sluiceways and through the central pier. The duct carries the interconnecting fuel and compressed-air pipes, together with electric cables and telephones. The suction and delivery pipes of the pumps are below engine-floor level, that is, below O.D. The delivery pipes of Nos. 1 and 3 pumps discharge into the sluiceways between the outer and inner sluice-gates. No. 2 pump delivers direct into the tide. Each engine-house has its own set of auxiliary engines and generators, but it is arranged that each can serve either engine-house by means of valves and piping carried through the reinforced-concrete duct.

The pumps each have a designed output of 840 tons of water per minute delivered against a static head of 10 feet when running at a speed of 84 revolutions per minute. At lower static heads the output is increased up to 1,000 tons per minute. At higher static heads the quantity decreases if the pumps are run at constant speed. In order to increase the output at the higher static heads the engines are arranged to run at higher speeds when necessary.

The discharge-branch of each pump has a diameter of 8 feet 6 inches with independent suction-branches 7 feet in diameter at the junction. The ends of the suction-pipes are fitted with bellmouths 10 feet 6 inches in diameter. The pumps are of the double-entry shrouded pattern with Francis blading and are 7 feet 11 inches in diameter over the shrouds, with a tip width of 2 feet 11 inches, the ratio between the eye-diameter and the tip-diameter being 1·25. The entry-speed of the water is low in order to avoid cavitation when pumping from a low drain-level. Guides are placed at the eye of the impeller in order to ensure radial entry and to provide support for the inner end of the bearings carrying the shaft and impeller, which by this means is well supported within the pump.

Some of the unusual points in the design and manufacture of the pumps may be of interest. When built up the overall height of each pump is 23 feet 6 inches, with a length over the shaft and outside bearings of 28 feet 3½ inches. To facilitate casting, machining and transport, the volute of the pump was made in four sections, each comprising two parts jointed through the vertical centre line, the largest being the part containing the smallest section of the volute, the cut-water and the discharge branch. The casting-weight

of this section was 11 tons 14 cwts., and the other volute sections in order of their development weighed 5 tons 12 cwts., 9 tons and 11 tons 13 cwts. The suction-branches are in two parts; the top half weighed 3 tons 5 cwts. and the bottom half 4 tons 12 cwts. The impeller was cast in one piece and weighed 10 tons, and when keyed to its shaft this formed the heaviest lift, namely, 14 tons. When keyed up, trued and balanced it was considered advisable to transport and erect this item in one unit, and the doors of the engine-house were specially designed to admit it.

In the making of these pumps the foundry-work followed the normal practice for heavy loam castings, 1 per cent. nickel being used in the mixture in order to ensure soundness. Every casting came out perfectly sound and matched splendidly, which, when it is realized that as much as 2 inches had to be allowed for cooling-contraction on some of the sections, was no mean achievement. For machining the joints of the volute sections a special milling and drilling machine was built with an independent motor-driven head. The boring of the built-up volute was done on a standard machine.

Attached to the discharge-branch of each pump is a Glenfield & Kennedy electrically-operated sluice-valve 8 feet 6 inches in diameter, designed for a working pressure of 22 feet head and tested to 60 feet head. It is made in cast iron, the body being in two parts. The doors are of the parallel-face type with gunmetal sealing-rings. The valve is operated by means of an electric motor geared to the screw through spur and worm reduction-gears, which are automatically lubricated. A particular feature of the gear is an automatic safety-device, which has been provided to eliminate the possibility of accidentally switching on the motor while the handle for emergency manual operations is in engagement. This device takes the form of a housing surrounding the squared end of the operating-shaft, and is closed by means of a hinged cover, in the hinge of which is incorporated a switch connected in series with the motor contactor-gear. On opening the cover to engage the operating-handle the contactor-circuit is broken, and the motor cannot be started until the circuit is again completed by removing the handle and closing the cover completely.

Two speeds for manual operation are available on the valve, one incorporating the large reduction-gear for opening the valve from its fully-closed position under full head, and the other involving the smaller reduction-gear for use when the valve is being operated under balanced conditions. The overall height of each of these valves is 24 feet 8½ inches and each weighs about 34 tons. The valves are housed in a pit, access to which is provided by means of a

vertical ladder. On the suction side of the valve a drain-cock is provided to empty the water between the pump-spindle and the main sluice-valve in times of frost.

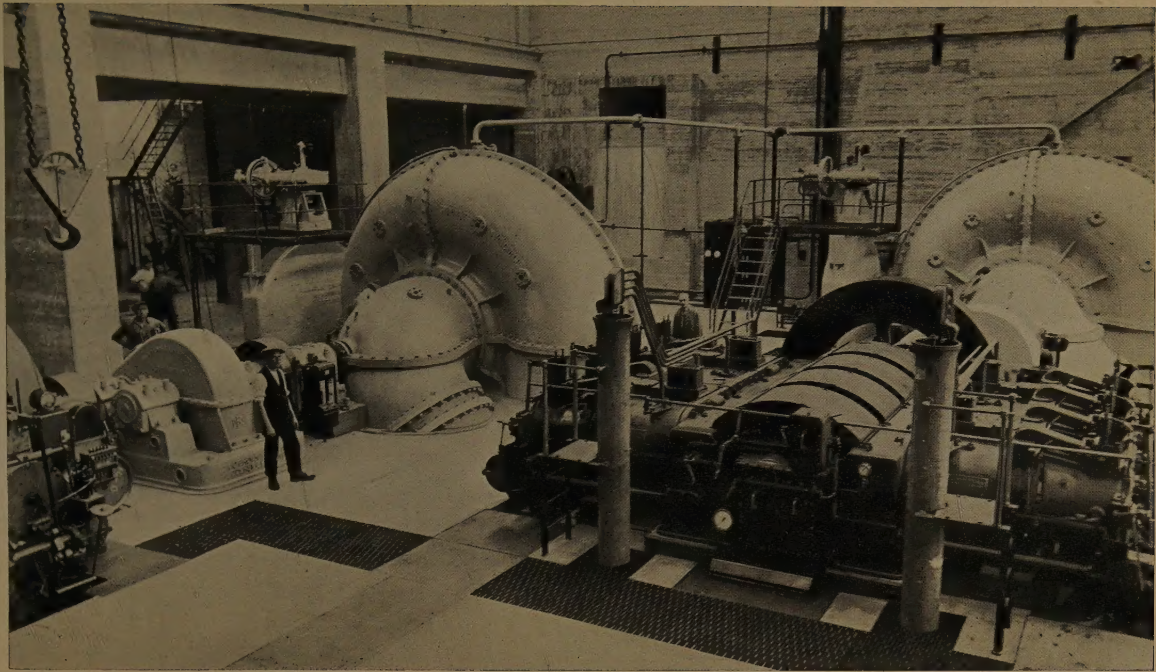
The engines drive the pumps through single-reduction gearing, designed and manufactured by David Brown & Sons, Ltd., of Huddersfield. The gears were designed to transmit the following powers:

1,000 HP.	at a speed reduction of from	225	to 94·5	revolutions per minute.
900 ,,	,, ,,	200	,, 84	,, ,,
770 ,,	,, ,,	171·4	,, 72	,, ,,

The pinions were made from high-carbon forged-steel rings, shrunk on to solid forged medium-carbon-steel shafts, with hob-generated double-helical involute teeth. The low-speed wheels with which they mesh consist of two high-carbon forged-steel rims shrunk on to cast-iron centres, which in turn are pressed and keyed on to low-carbon forged-steel shafts. The gear-centres are 2 feet 8 inches apart and there are fifty-nine pinion-teeth and one hundred and forty-one wheel-teeth, of 1 inch circular pitch. Splash-lubrication is supplied for the gears and ring-lubrication for the bearings. Flexible couplings of the makers' own design are fitted on both shafts of the gear-box. The oil-engines were made by the Premier Gas Engine Company and are of the four-stroke horizontally-opposed type, having eight cylinders of 26-inch stroke by 18-inch diameter, with a 9-ton flywheel. Each engine (*Fig. 4*) weighs about 65 tons. The first engine was submitted to a continuous test-run lasting for 7 days and nights at the works, with satisfactory results. Each engine is fitted with electric barring-gear, and pyrometers are attached to each exhaust pipe and are connected to an indicator placed on the engine-room wall. The cooling system is of the open type and thermometers are fitted in the circulating-water outlets from each cylinder-jacket. The engine-houses are heated by two large coke stoves. In addition, electric heaters are arranged under the cylinders to keep the water in the cylinder-jackets and the oil in the cylinders at a reasonable temperature while the plant is not operating during frosty weather.

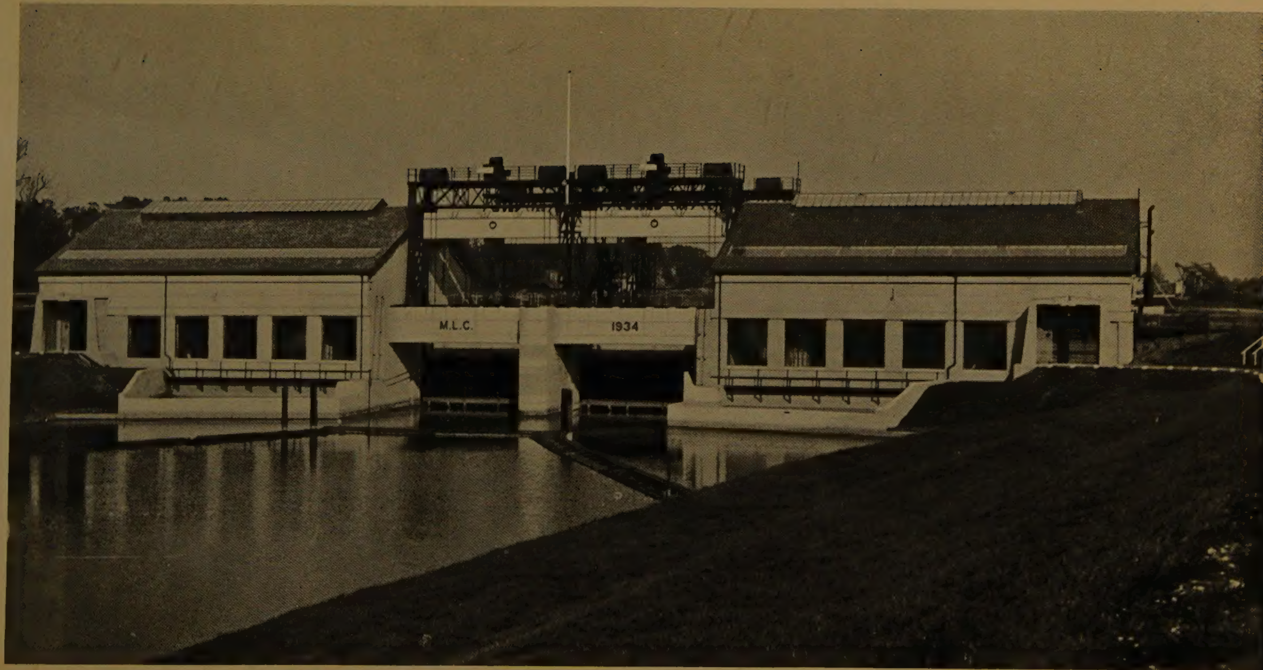
The main sluice-gates are of the vertical type, 36 feet wide and 19 feet high, with roller-wheels fixed to the gates, and are provided with double staunching balanced by counterweights; they are placed between the north and south engine-houses. The gates are electrically operated, with direct and remote control in the engine-houses, and they may also be operated by hand. The gates were supplied and erected by Messrs. Ransomes & Rapier, of Ipswich. They work in conjunction with a reinforced-concrete bulkhead. The level of the

Fig. 4.



INTERIOR OF NORTH ENGINE-HOUSE.

Fig. 8.



VIEW OF SLUICES AND PUMPING-STATION FROM DRAIN SIDE.

sill is — 12·66 O.D. and the lintel of the bulkhead is 6·34 O.D. Each gate is designed to withstand a reversal of loads, that is, a high tide on one side and no water on the drain side, or *vice versa.*

There are two sluice-gates in each sluiceway, arranged about 55 feet apart (Fig. 5, Plate 1). The centre pier is 112 feet long, 32 feet high and 7 feet thick, and is so designed that one of the sluiceways between the gates can be full and the other empty. When discharge is by gravitation, the sluice-gates are all lifted; but when the pumps are working the outer or tidal gates are lifted and the inner gates are closed. By arranging the discharge outlets from Nos. 1 and 3 pumps between the pair of sluice-gates, and by regulating the outer or tidal gate, the necessary operation for sluicing the tidal outfall channel is accomplished. Each of the sluice-gates weighs 28½ tons, and is connected by a series of sheaves to reinforced-concrete counterbalances, which weigh about 56 tons and travel half the distance of the gate. In order to facilitate inspection and repair, the sluice-gates may be lifted so that the bottom edge is level with the coping, which is 19·34 O.D. Each sluice-gate is built up of three girders, which carry vertical channels supporting the skin-plate.

The gates are operated by means of an electrically-driven central crab on each of the four spans, which drives the hoist-barrels through a cross-shaft and spur gearing. Auxiliary hand operation is arranged for in the event of failure of the current. Limit-switches are provided which prevent the gate over-running at either end of its travel; these switches are situated in the central crabs and are operated by a tappet geared down from the cross-shaft. The driving-motors are each 10-B.HP. compound-wound machines, mounted on top of the central crabs and connected to the gearing by a roller-chain. They are supplied with 220 volts D.C. In the engine-houses float-controlled electrically-operated illuminated indicators have been installed to register the level of water on the tidal and non-tidal sides of the sluice, and the height of each gate above the sill. The electrical control-gear is of the reversing-contactor type, the controllers being situated in the engine-house and operated, either from the house or from a position near the central crab, by three push-buttons.

Provision has been made for temporary gates, and grooves have been built into the piers on both the river and drain sides of the sluices; those on the drain side are plain grooves suitable for stop-logs, while on the tidal side the grooves are provided with rails and corner angles suitable for the reception of steel gate-sections. The end crab-bearers which run across the overhead girders are extended on the river side to carry a runway-joist for the purpose of placing

the temporary gates in position, the overhanging ends being supported by steel columns built up from the piers. At lintel-level a 3-inch-diameter heating pipe has been built in the concrete and carried from the north to the south engine-house, so that in time of heavy frost the lintel can be heated; freezing of the joint between the top of the sluice-gate and the bottom of the reinforced-concrete bulkhead can therefore be prevented.

Each engine-house is provided with a 15-ton overhead travelling crane of 62 feet span, a switchboard where all electrical controls are grouped, and house-drainage and circulating-water pumps. Fuel-oil storage is provided in two steel tanks each of 50 tons capacity, interconnected and founded on a reinforced-concrete raft at about coping-level. The tanks are adjacent to the south engine-house. The oil is delivered in bulk and is pumped into the fuel-tanks from the road through a pipe-line about 150 yards long. From the tanks the oil gravitates to the service-tanks provided for each engine in the south and north engine-houses, where the level is controlled by automatic valves.

Construction.

The Middle Level Board decided to carry out the constructional work by direct labour, under the direction of the Author. Before this could be undertaken, and in order to comply with the conditions laid down by the Unemployment Grants Committee, a camp to accommodate 150 men from the distressed areas was erected, complete with sleeping accommodation, dining-halls, kitchens, ablution- and bath-huts and recreation hall. Trial boreholes were taken at the positions shown on Fig. 1, Plate 1. The sections at the boreholes are shown in Figs. 6, Plate 1.

At the outset it was decided to take over the two 44-B.HP. Crossley engines and Crompton generators from the main contractors and to place them in a temporary engine-house, thus providing electric power for excavating, pile-driving, pumping and concrete-mixing.

It was advisable to keep the new structure as near the River Ouse as possible in view of the foundations and the nature of the material to be excavated. On the other hand, it was equally important to keep the existing sluice, built in 1880 on the diversion, functioning during the work, as this was the only means of evacuating the flood-water from the area during the construction of the new sluice. The site selected for building the new sluice was in the silted-up channel of the original Main Drain. Since 1862 this disused channel had silted up to a depth of 22 feet, but it was still subject

to tidal influence during high spring tides, and before construction could commence it was necessary to put a dam across it in order to isolate it from the tide.

An embankment was tipped across the old outfall-channel and through this Larssen steel sheet-piles of No. 2 section, B.S.P., 55 feet long, were driven in pairs by a 3-ton McKiernan-Terry steam-hammer. The clutches were well greased before driving, which facilitated the withdrawal of the piles in their entire lengths on the completion of the works. The excavation of the old channel was carried out with a machine which is believed to be new to this country, namely, the Henderson drag-scraper, operated by a 60-HP. motor. Pumping the excavated material was considered, but the spoil-dump was limited owing to the high price of land. A trial was made with dragline-dredgers, but the material to be excavated was unable to bear the weight of the draglines, even if they were supported on mats. The material to be excavated had a fairly hard but thin top layer, but below this crust it was of the consistency of thick porridge so that when a weight was placed on it the surface was liable to fail suddenly.

The Henderson equipment consisted of a tower for the operator, through which the spoil was allowed to drop into "Jubilee" wagons. The bucket or scraper had two sides and a top, but no bottom. It was operated by a cable, and at the back end it was attached to another cable which passed through the tail- and carriage-pulleys and back to the hauling tower. The scraper was arranged to slide over the material and to fill itself gradually, the material being scraped by the sides and retained by the top. When full it was hauled up the ramp to the grid. The machine worked to a width of 220 feet and to a depth of 34 feet. The filled wagons were then hauled away in batches of ten to the spoil-heap.

Owing to constant slips and to the seepage of tidal water from the diversion-channel through the strata of peat, it became necessary to enclose the entire site of the new structure. No. 2 Larssen steel piling was used, each length being about 30 feet, and this dam was left in place after completion. It may be of interest to note that during the excavation of the site the earth embankment, or temporary dam, moved and distorted the steel piles in the dam so much that the dam had to be anchored back with four steel-wire ropes $2\frac{1}{2}$ inches in diameter attached to a series of anchor-piles.

Excavation was carried down to the level of the underside of the reinforced-concrete raft shown in Fig. 5, Plate 1, and then trial-pits were sunk to the Kimmeridge clay, about —23 O.D. After examination of the Kimmeridge clay it was thought there was a possibility of founding the new structure on a reinforced-concrete

raft on the Kimmeridge clay. However, it was considered advisable to test the bearing-capacity of the clay by driving a pile. A trial reinforced-concrete pile, 35 feet long and 14 inches by 14 inches, was used with a 2-ton monkey, and it penetrated the Kimmeridge clay 34 feet before a reliable set was reached. In view of this it was decided that a piled foundation would be the most reliable, as the pumping machinery is placed at the extreme ends of the structure and any settlement or subsidence might upset the alignment of the pumping units and of the sluice-gates. Ultimately, the whole structure was supported on 14-inch by 14-inch reinforced-concrete piles varying in length from 35 to 46 feet. Altogether one thousand three hundred and eighty-nine piles were driven to support the structure. Raking piles, to a batter of 1 in $2\frac{1}{2}$, were driven in both directions to take the thrust of the sluice-gates and the reaction from the pumps. During the driving of the raking-piles it was noticed that some of the vertical piles, which had previously been driven to the required set, had lifted a distance of from 2 to 4 inches. These vertical piles were afterwards submitted to a much more severe test, and were passed as satisfactory without any further measurable movement.

All the reinforced-concrete piles were cast near the aggregate-washer and grader, and were arranged so that they could all be lifted by a hand crane and transported to the site. Great care was taken to see that all the reinforcing links were made the same size, and that all were equally taut when the reinforcement was set up in the moulds before the concrete was cast. The piles were numbered and marked. A record was kept of the position, driving and set of each pile. It was arranged that every pile was to mature 10 days before being driven, but, by mistake, one pile was driven in 5 days without damage. Mass-concrete and reinforced concrete for the foundations and engine-houses were machine-mixed as near the site as possible; clean water from the water-mains was used for concrete-mixing in all cases.

At the site, the piles were handled and pitched against the piling-frames by three derrick-cranes. One of these was electrically operated, the other two being steam-driven. The capacity of two of the cranes was 5 tons at 75 feet radius, the third crane being able to lift 5 tons at 80 feet radius. Two of the cranes were placed on the north side opposite the engine-houses, and the third was erected opposite the central pier on the south side. These cranes handled the excavation inside the Larssen piling, as well as the concrete aggregate, the sections of the pumps and the piping. They also assisted in the assembly of the principals for the roofs and superstructure of the sluices.

The concrete aggregate was raised from a local gravel-pit, about 5 miles from the site. It was washed and graded on the site with a machine made in the Commissioners' workshops. The gravel as raised contained too much fine sand, and experiments were carried out to ascertain the mixture with the least percentage of voids. From time to time this was checked by the Resident Engineer's staff.

In excavating the trial pits down to the Kimmeridge clay, a thin layer of fine sand and a layer of peat were found overlying the clay, varying from 3 to 9 inches in thickness. After driving the reinforced-concrete piles it was decided to excavate down to the Kimmeridge clay and to fill in with mass-concrete up to the underside of the reinforced-concrete raft which was supported on the piles. In view of further movement in the surrounding banks it was deemed expedient to carry out this excavation in sections, compartments being formed by driving Larssen No. 2 piling and strutting it. The first section undertaken was for the whole length of the central pier for a width of 20 feet. This, when concreted in and consolidated, was used for strutting off other sections which were treated in a similar manner. The pile-heads projecting above the mass-concrete were then cut off to the right level, and the bars were stripped of concrete in order to get a good connection with the reinforcement in the reinforced-concrete raft.

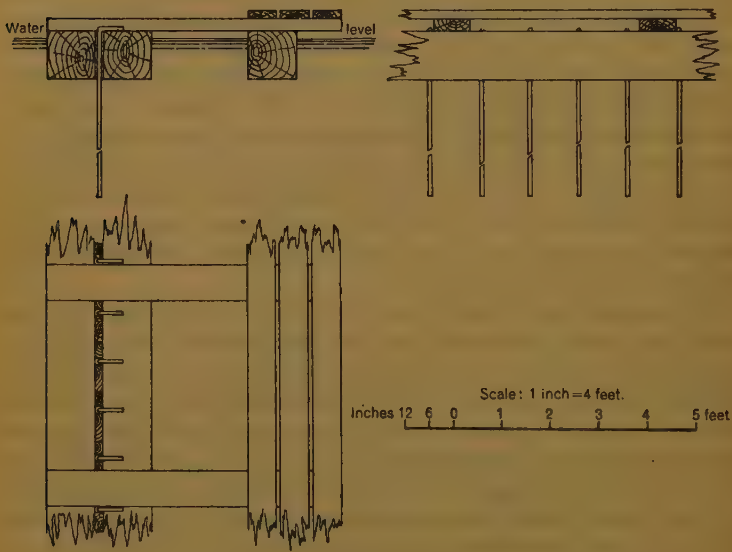
On the reinforced-concrete raft, which is 3 feet thick, preparations were made for assembling the lower sections of the pumps and sluice-valves, together with the suction and delivery pipes. Concrete stools were cast on the raft to support the pump-sections, sluice-valves and pipes, and when they were lined up they were enveloped in 6-to-1 mass-concrete. To prevent distortion of the pumps a dummy impeller-shaft was used. Engine-room floor-level is about 3 feet below the centre-line of the impeller-shaft. At a later stage the foundations for the engines and gear-boxes were set out with the necessary holes cored in the concrete for the foundation-bolts. The building proper was founded on the reinforced-concrete raft with stub-bars intimately connecting the reinforcement of the raft and vertical walls. The central pier was constructed first and spaces were left for the interlacing of the reinforcement of the bulkheads and cooling-tanks, which are both constructed of reinforced concrete. Similarly, spaces were left in the two walls of the sluice-ways, which form the walls of the engine-houses.

The cooling-tanks are situated across the sluiceway, the top of the tanks being level with the coping. Water is pumped into these tanks from the cooling-pond situated over the flumes. The tanks are fitted with baffles so that any silt or matter in suspension

is precipitated. The cooling-water then gravitates through the cylinder-jackets and then discharges into the cooling-ponds. The overhead travellers are supported on reinforced-concrete columns which are incorporated in the outer walls of the engine-houses.

The roof of each engine-house is 89 feet long and has a span of 64 feet, with an annexe in reinforced concrete at coping-level. The principals are of steel construction. The roof is covered with close boarding and asbestos tiles. A lantern-light is provided for a length of 65 feet in each roof, and additional lighting is obtained by glass in the slopes of the roof. Each engine-house has a main

Figs. 7.



entrance with a portico about 12 feet by 8 feet at a level of 7·24 O.D. on the drain side; the doors are constructed of teak. In addition, a bulkhead-entrance with a staircase is provided from coping-level near the tidal sluice-gates (Fig. 5, Plate 1). It will be seen that a vertical lip is provided at the end of the apron to prevent scouring, and this has so far proved successful. The apron on the tidal side is reinforced and incorporated in the converging vertical retaining walls, but it is not supported on piles. Under the concrete lip steel sheet-piles were driven across the outfall channel (Fig. 5, Plate 1). On the non-tidal side the apron is below sill-level and it was considered that mass-concrete, with mass-concrete beams, would be sufficient.

To prevent floating or semi-submerged objects from getting into the pumps, floating booms are provided which are moored to piles. The booms are constructed of 12 inches by 12 inches pitch-pine baulks (*Figs. 7*). The screen or grid is formed of 1-inch steel bars 7 feet long, which have one end bent at right angles for a length of 6 inches. These bars are introduced between two 12-inch by 12-inch logs which are placed about $1\frac{1}{2}$ inches apart and divided into pockets 2 inches long. The bars form a grid, and as the booms are laid across the stream obliquely the bars of the grid, are, in effect, at about 12-inch centres. One boom is placed about 50 feet from the entrance to the flumes and the other is about 250 yards upstream. The booms rise and fall with the varying water-level; and should the steel bars touch the bottom they simply slide up and project temporarily above the boom-level.

Removal of Hawkshaw Dam.

After the new structure was completed it was necessary to remove the temporary dam on the tidal side and also the Hawkshaw dam, which had been in position since 1862, on the non-tidal side. The removal of the temporary dam presented little difficulty as far as the earth portion was concerned, but at first the Larssen steel piles were troublesome. Eventually, by using a set of three- and two-sheave steel blocks carried back to a steam-winch which exerted a constant pull, and simultaneously using the McKiernan-Terry hammer fitted with extractor-gear, all the piles were pulled out with very little cutting.

It was considered that the best way to remove the Hawkshaw dam would be in the dry, as the siphons and the inlet- and discharge-valves were intact under water, and were bolted and concreted in place. An earth embankment was accordingly tipped about 200 feet upstream of the Hawkshaw dam, and the water imprisoned between the two dams was pumped out gradually. Any settlement of the new dam was made up and the slopes stabilized by sacks filled with earth. In due course the Hawkshaw dam was dried up, and then the earth filling was removed and the timber structure dismantled. All the timber piles were drawn and found to be in good condition, excepting the heads, which had been exposed to the weather. The piles were hewn Danzig without any trace of tar, creosote or other preservative, and the mortise and tenon on the caps and piles were perfectly sound. The bulk of these timber piles have been redriven elsewhere. The straps and bolts were wrought iron, but these were heavily rusted. The cast-iron siphons, pipes and valves were in good condition.

The cost of the whole Scheme was £224,000, and the completed work is shown in *Fig. 8* (facing p. 385).

The Author wishes to express his acknowledgments to the Resident Engineer, Mr. D. G. Hill, Assoc. M. Inst. C.E., also to his two principal assistants, Messrs. G. E. Buchner and L. I. Clark, Assoc. MM. Inst. C.E.

The Paper is accompanied by ten sheets of drawings and by twenty-six photographs, from some of which Plate 1, the page of half-tones, and the Figure in the text have been prepared.

Paper No. 5043.

"The Effect of Flood-Relief Works on Flood-Levels below such Works."

By Eric Chester Hillman, M.C., B.Sc., Assoc. M. Inst. C.E.

TABLE OF CONTENTS.

Introduction.

The carrying out of improvements to rivers or channels for the purpose of flood-alleviation, whether combined with embankment-systems or otherwise, will, in most cases, alter the conditions of flow below such works. While, however, this fact is generally recognized, the reasons for the alterations may not be so well understood, and it is the object of this Paper to endeavour to analyse the reasons for this result and to ascertain the effects on unprotected areas due to the elimination of flooding from protected areas above them.

Flood-protection works may usually be divided into two categories:

(1) Channel-improvement or by-passing, with the object of reducing flood-levels locally.

(2) Embankment-systems, with the object of excluding flood-waters from certain areas.

The effects of such works on flood-levels immediately below them can conveniently be studied separately, and in any scheme combining both classes of works the final result will be a combination of the separate effects.

Channels.

Channel-Improvement and By-Passing.

Either widening and deepening the channel, or cutting a separate by-pass channel parallel to the main channel, is equally effective in permitting a given quantity of water to flow through at a lower level than in the unimproved channel. A by-pass channel may be preferable to widening and deepening a natural stream, on account of the silting which is almost certain to take place in a natural stream which has been artificially enlarged. A natural river-channel in an alluvial bed will invariably be found to have a smaller cross-sectional area than is necessary to pass the full flood-flow from its catchment, and the channel would appear to become stabilized, both in length and in cross-sectional area, in accordance with the nature of the material through which it passes. Any interference or alteration of the natural conditions immediately upsets the regime of the river, which at once sets to work to revert to its original state. For instance, in the case of a river-bend being short-circuited by means of a "cut-off," scour of the banks below the bend takes place due to increased velocity, and expensive revetment becomes necessary. Again, when a natural river-channel is deepened and widened, the larger cross-sectional area causes a reduction in velocity, silt is therefore deposited more rapidly, and shoaling commences.

A by-pass channel, controlled either by sluices or a weir in such a manner that no flow takes place in it during normal times, but only during floods, will not be seriously affected by silt, and the stability of the natural river-channel will be maintained. An alternative to the cutting of a separate by-pass channel is provided by setting back the artificial banks of a river, the land between the river and the flood-banks forming a normally dry channel, but of sufficiently large cross-sectional area to carry, during floods, the excess flow which the natural channel is unable to accommodate.

The capacity of the by-pass channel may have to be at least as great as, if not considerably greater than, that of the river itself. From a study of the normal and flood-discharges of a number of rivers in alluvial valleys, it is the Author's opinion that generally, in England, the ratio of high-flood flow to "bank-full" discharge may roughly be taken as three to one; it follows from this that as a general rule the flood-channel must have about twice the capacity of the normal river-channel. (By "bank-full" is meant the full capacity of the natural river-channel, without overflow.)

In designing a by-pass scheme, each case must naturally be considered on its merits. It is, however, essential that proper allowance

should be made for the passage of flood-flows, and quantitative data must be obtained before a sound scheme can be prepared.

Effect of By-Pass-Channel Flow on Flood-Levels.

Seeing that a by-pass channel may have to be as large as, or even larger than, the river-channel itself, first considerations may lead to the belief that, in consequence, at least double the quantity of water will flow, thereby increasing the flood-level below the by-pass.

The reason for this belief may be found in the not uncommon experience that when two taps are turned on more water flows than when only one tap is used. This, however, is only true if the pipe to which the taps are connected is capable of conveying more water than one tap alone is capable of discharging. In other words, if one tap is able to discharge all the water that a pipe is capable of delivering, the addition of another similar tap to the pipe will not enable more water to be obtained; all that will happen is that the flow from each tap will be halved.

Similarly, if one channel, in which a certain fixed quantity of water is flowing, is bifurcated into two channels, the sum of the flows in the separate channels will be equal to the flow in the single channel. Again, if the branch channels are identical with the single channel in size, slope and friction-coefficient, it follows that because the flow in each is equal to half the flow in the single channel, the depth of water in the branch channels will be less than that in the single channel.

This argument assumes that the flow in the single channel is unaltered as a result of the bifurcation. This being the case, it is necessary to explain why it should be so, and the more familiar effect of a weir across a stream will perhaps enable the matter to be more clearly understood.

When a weir is placed across a river, water is ponded up behind the weir until a certain level is reached at which the flow over the weir is exactly equal to the flow in the river above the weir. If the water-surface levels above the weir are plotted in longitudinal section, they will be found to lie on a curve more or less asymptotic to the original river-surface gradient, the difference in level decreasing rapidly or slowly according to whether the original slope is steep or flat. The important point, however, is that this "backwater-curve" eventually merges into the original gradient, at which point the effect of the weir on the river vanishes. Above this point, which may be termed the "limit of influence of the backwater-curve," the discharge of the river can in no way be affected by the weir.

In the same manner, if, instead of building a weir, the river is deepened or by-passed, the surface-level will be lowered, and a similar curve, known as a " draw-down curve," will be produced. Here, again, the differences between the reduced levels and the original gradient decrease progressively upstream until a point is reached at which the effect vanishes altogether.

From this it is clear that at some point above either a weir or a by-pass channel, the effect of the local increase or decrease in the level of the water-surface vanishes. Therefore, neither a weir, nor a by-pass, can in any way alter the discharge of a river above this " limit of influence." Having established the fact that no more water can be drawn off the catchment than the quantity which is flowing in the river above the limit of influence of the " drawn-down curve," it will be seen that the effect of a by-pass channel is merely to cause a local reduction in the flood-gradient; it in no way alters the total discharge.

With regard to flood-levels below the by-pass (that is to say, below the point at which the by-pass channel rejoins the river), as the discharge is unaltered, the flood-levels will also be unaltered, and the effect of the by-pass will be nil.

Embankment-Systems.

River-flood embankments are constructed for the purpose of excluding flood-waters from low-lying land in the vicinity of a river.

Such land, which is normally dry, but is liable to inundation during floods, may act in one or more ways:

(*a*) It may function purely as an uncontrolled storage-reservoir, the flow to and from the river being governed entirely by the relative levels of the water in the river and in the " reservoir."

(*b*) It may act as a by-pass channel, allowing flow which cannot be accommodated in the river to take place over the land.

(*c*) It may, and usually does, combine the functions of both (*a*) and (*b*).

An example of (*a*) would be the valley of a tributary stream, the catchment of which is entirely bounded by high ground, and which is only connected to the river at one point.

An example of (*b*) would be a long narrow strip of land running parallel to the river, having little storage capacity, and into which excess flow from the river can enter at its upper end, the flow rejoining the river at the lower end of the strip.

A broad expanse of land, perhaps connected to the river at various points, or even throughout its whole length, and acting both as a by-pass channel and storage-reservoir, would be an example of (*c*).

It has already been shown that a by-pass channel can have no effect on the flood-level below the point at which it rejoins the river, and therefore for the purpose of this investigation function (*b*) of a flooded area may be ignored. Consideration must now be given to the effect of a storage-reservoir of type (*a*) only.

The Use of Reservoirs for the Purpose of Flood-Relief.

When a reservoir is constructed to impound water at the head of a river-valley, all the run-off from the catchment above the reservoir is collected, provided that no spilling takes place. If no compensation-water is given, the river immediately below the reservoir may be robbed of all its flow, including floods.

In practice, however, although all the run-off may be collected, compensation-water is allowed to flow down the river, the flow being controlled by sluices in the dam. The effect of this on the river may be beneficial, in that the flow is changed from a fluctuating flow, with extremes of floods and droughts, to a steady flow. A controlled reservoir may, therefore, be capable of entirely eliminating floods in the river-valley immediately below it.

An uncontrolled reservoir, on the other hand, may operate in such a manner as greatly to augment floods. It frequently occurs in nature, for instance, that a river-valley becomes dammed by ice or debris piling up against some obstruction, and a large volume of water becomes temporarily stored in the reservoir thus created. This dam eventually bursts, and the whole flow, suddenly released, rushes down the valley, causing a greater flood than would have occurred from rainfall only.

Again, even a properly-constructed reservoir, with spill and sluices, may be practically useless for the purpose of reducing floods if it is not controlled with that end in view; that is to say, it is almost useless if the reservoir is full immediately prior to a heavy storm over the catchment, as in this case there will be little or no extra storage-capacity available at the critical time, and practically the whole flood-flow will be passed into the river over the spill of the reservoir.

From the above it will be seen that an uncontrolled reservoir may be useless, and even worse than useless, as a means of flood-alleviation.

Controlled Flood-Relief Reservoirs.

It is clear that, for efficient flood-control, the capacity of a reservoir must be such as to be able to store all the water flowing off the catchment in excess of the maximum flow that can safely be permitted to pass down the river.

To take an actual example, it is proposed to estimate the required size of a hypothetical reservoir to be constructed near Nottingham, for the purpose of so regulating the flow of the river Trent, in a flood similar to that of May, 1932, that it would not overflow its natural banks. From 22 May to 1 June, 1932, the mean rate of flow is computed to have been 15,022 cusecs. This river can, without overflowing, carry approximately 9,000 cusecs, and there is therefore a balance of 6,022 cusecs for 11 days as the mean excess flow that would have to be diverted into the reservoir.

One cusec will fill approximately 2 acres of land to a depth of 1 foot in 1 day. The reservoir-capacity required would therefore have to be 6,022 × 2 × 11, or 132,484 acre-feet. This is equivalent to 207 square miles of country flooded to a depth of 1 foot, or 69 square miles flooded to an average depth of 3 feet.

The effect at Nottingham of such a reservoir, properly controlled, would be to reduce the flood-level from 79·0 O.D. to about 73·0 O.D., but the utter impracticability of such a proposal is obvious. This argument has been introduced for the purpose of showing that a reservoir of 6,000 acre-feet capacity, which is roughly the storage-capacity of the area which it is proposed to protect by a flood-protection scheme, could, even if controlled, have little effect on the flood-levels below the scheme.

It is now necessary to study the manner in which a flood-relief reservoir must be controlled in order that it shall efficiently serve its intended purpose. Floods move down a river-valley in the form of one or more waves, that is to say the flood-levels gradually rise to a peak, remain at peak-level for a period, and then subside. It frequently happens that a second or third peak follows the first peak, the shape of the hydrograph depending on the intensity and distribution of rainfall over the catchment.

To take an example, Table I shows the computed discharges at Nottingham in the May, 1932, flood.

In this flood it will be seen (*Fig. 1*, p. 400) that there were two peaks, occurring respectively on 24 and 30 May. It will also be noticed that the former peak was much sharper than the latter.

The flow that can just be accommodated in the river without overflow being 9,000 cusecs, it follows that the flow into the storage-reservoir on 22 May should have been 5,660 cusecs, on 23 May 11,120 cusecs, and so on. If less than 11,120 cusecs were to flow

into the reservoir on 23 May, more than 9,000 cusecs would flow down the river, and flooding would occur. On the other hand, if more water were to be taken to the reservoir, the river-flow would have been unnecessarily reduced.

TABLE I.

Date.	Discharge: cusecs.	River-capacity without overflowing: cusecs.	Excess discharge to reservoir: cusecs.	Flow returned from reservoir to river: cusecs.
21 May, 1932	3,600	9,000	—	—
22 ,,	14,660	,,	5,660	—
23 ,,	20,120	,,	11,120	—
24 ,,	22,000	,,	13,000	—
25 ,,	17,660	,,	8,660	—
26 ,,	14,200	,,	5,200	—
27 ,,	11,000	,,	2,000	—
28 ,,	12,900	,,	3,900	—
29 ,,	13,700	,,	4,700	—
30 ,,	14,000	,,	5,000	—
31 ,,	13,400	,,	4,400	—
1 June, 1932	11,600	,,	2,600	—
2 ,,	7,200	,,	—	1,800
3 ,,	5,900	,,	—	3,100
Mean flows for 11 days	15,022	9,000	6,022	—

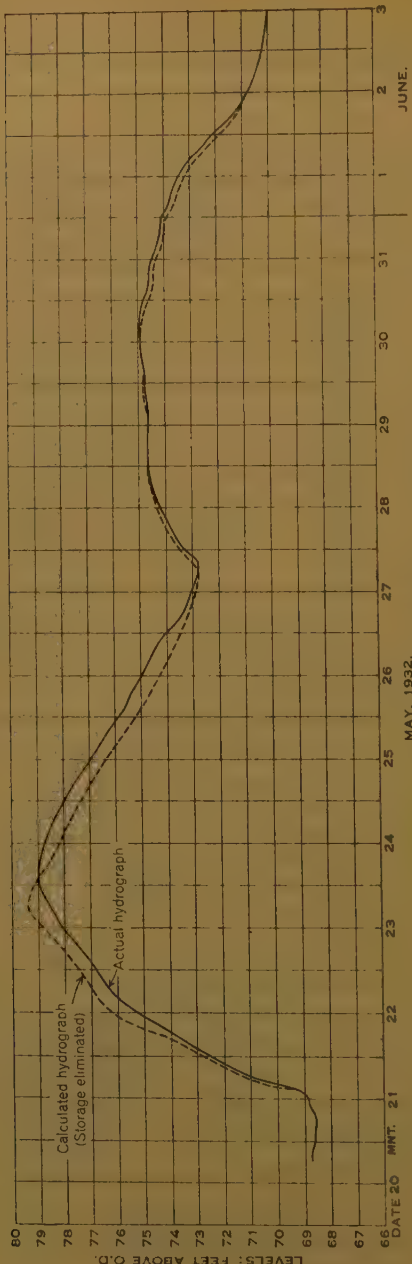
The flow into the reservoir, then, has to be controlled exactly to accommodate the excess flow, keeping a constant flow of 9,000 cusecs in the river. Only after the flood has subsided can the reservoir be allowed to discharge its stored water back into the river. Thus on 2 June, when the river-flow had fallen to 7,200 cusecs, the reservoir-sluices could have been opened to pass 1,800 cusecs into the river, but no more. On 3 June 3,100 cusecs could have been passed, and so on until the reservoir was again empty.

Effect of Uncontrolled Reservoir-Storage.

It has already been stated that an unprotected area liable to flooding acts as an uncontrolled reservoir, the flow of water into and out of the area being governed by the relative levels of water in the river and in the reservoir. For the purpose of this investigation, the reservoir is assumed to be open to the river at one point only, this point hereafter being referred to as "the junction." The flood will be considered in three stages:

(i) The rising period.
(ii) The falling period.
(iii) The peak period.

Fig. 1.



HYDROGRAPH OF MAY, 1932, FLOOD AT NOTTINGHAM.

(i) *The Rising Period.*—On a rising flood, the river-flow increases until the discharge becomes too great for the natural channel to accommodate. Water then overflows the banks, and commences to fill the storage-reservoir. Flow cannot take place into the reservoir unless the level of the land, or the level of the water over the land, is below the level of the water in the river at the junction.

When this flow into the reservoir is taking place it is necessary to consider what will be the effect on the flood-level below the junction. It is not known at the moment what quantity of water is flowing into the reservoir; let this quantity therefore be denoted by X, and let the flow in the river above the junction be denoted by F. It is clear that the flow in the river below the junction will be $F - X$, or, in other words, the effect of the flow into the reservoir will be to cause the flood-level in the river below the junction to be lower than it would have been if the full flow F had been passing.

(ii) *The Falling Period.*—Consider now what happens when the river-flood above the junction is subsiding. A time will come when the level in the river at the junction becomes less than that of the water in the storage-reservoir, with the result that water will flow from the reservoir back into the river. Denoting this flow by X', and the river-flow above the junction by F', it will be seen that the flow in the river below the junction will be $F' + X'$, and the effect will be that the flood-level in the river below the junction will be higher than it would have been if the flow F' only had been passing.

From the above, it is clear that the effect of an uncontrolled storage-reservoir on the flood-level below the reservoir is a reduction during the rising period of a flood, and an increase during the falling period.

(iii) *The Peak Period.*—The crucial and most difficult part of this investigation is now reached; namely, the effect at the actual peak of a flood.

For the purpose of argument, an hypothetical case will be assumed in which the flood, after rising to a peak-level, remains constant at this level for a very long period. If this should happen, it is clear that, as the reservoir is connected to the river, and is assumed to be of limited capacity, the level in the reservoir will in time become exactly equal to the level in the river at the junction. When this happens all flow from the river into the reservoir will cease, and the quantity X will become zero. The flow $F - X$ in the river below the junction will then be F only, and the flood-level in the river below the junction will be exactly equal to what it would have been had there been no storage-reservoir at all. In other words, in a flood whose peak level remains constant for a

considerable length of time, the effect on the flood-level below the reservoir is nil at the peak of the flood.

On the other hand, suppose that, instead of a flood whose peak-level remains constant for a long period, the case is considered of a flood which reaches its peak very rapidly, and immediately falls again. In this case the hydrograph of the flood above the junction is assumed to rise at a constant slope to its peak, and immediately to fall again, the diagram forming an acute angle at the peak.

At any time during the rising period, when water is flowing from the river into the reservoir, the reservoir water-level will be below that of the river at the junction, this condition continuing right up to the peak. Actually at the peak, therefore, in this case water will be flowing from the river into the reservoir, and the flow in the river below the junction will be $F - X$, with a corresponding reduction in level.

Let the peak-flow in the river above the junction be termed F_p. It is assumed that immediately after reaching its peak the river rapidly falls. This fall will very soon equalize the levels in the river and the reservoir, and the flow into the reservoir will then cease. At the moment that this flow ceases, however, the flow in the river above the junction is no longer as great as F_p. Therefore, up to the time that the levels become equalized, the flow below the junction is $F - X$, where X is a positive quantity; further, at the moment that the levels become equalized, X becomes zero, and the flow in the river is less than the full flow F_p.

From this it will be seen that, in the case of a rapidly rising and falling flood, the flow in the river below the junction can never quite equal the full flow F_p of the river above the junction, and the reservoir will have had some effect, however slight, in reducing the flood-level in the river below the junction.

From a consideration of these two extreme cases, in the first of which the peak-level is maintained for a long time and the reservoir has no effect, and in the second of which the river rises and falls very rapidly and the effect of the reservoir is definite, though small, it will be seen that it is impossible to generalize on the question. The effect of an uncontrolled storage-reservoir on the flood-level below it is therefore dependent on the shape of the hydrograph of the flood, and is a minimum when the peak is flat-topped, and a maximum when the peak is sharp.

Size of Uncontrolled Storage-Reservoir.

So far, it has been assumed in the investigation that a storage-reservoir of limited size is provided, which is capable of being filled to peak river-level providing the river remains at its peak for a sufficiently long period.

Suppose, however, that the reservoir is extremely large. It will then be capable of absorbing all the excess flow from the river, and the river-level will only rise to a height sufficient to permit this excess flow to take place into the reservoir. In such a case the river below the reservoir will be relieved of all floods.

On the contrary, assume the reservoir to be very small. Very little flow from the river will be sufficient to fill it, and, even if the peak of the flood is only of short duration, the relief due to the reservoir will be negligible.

From this it is clear that the effect of the reservoir is not only dependent upon the shape of the hydrograph, but also upon the capacity of the reservoir relative to the volume of water flowing in the river. Each case, therefore, has to be studied individually, the data required being the flood-hydrograph (as shown in *Fig. 1*), river-discharge curve (*Fig. 2*, p. 404), and a storage-capacity curve for the reservoir, giving the volume at different levels.

Calculations.

1. *The Flood-Hydrograph.*

The flood-hydrograph (*Fig. 1*) is obtained by plotting daily gauge-readings, reduced to Ordnance Datum, as ordinates, against time in days as abscissae. A smooth curve drawn through the points thus obtained will be approximately accurate. Greater accuracy will naturally be obtained if the readings are taken at smaller time intervals, the hydrograph obtained from an automatic water-level recorder of proved accuracy being the ideal.

2. *The Discharge-Curve.*

This curve (*Fig. 2*) connects river-heights as ordinates, with discharges, preferably measured in cusecs, as abscissae. Methods of measuring velocities and discharges need not be described in this Paper, but such measurements must be continuous throughout the whole period of the rise and fall of the flood.

3. *The Capacity-Curve.*

If the flooded area should act as a reservoir of type (*a*) only,[1] it may be that the flood-levels at all points over the area will be approximately equal at any given time. In such a case the capacity of the area at different depths may be calculated quite simply from land-contours, and the results plotted in the form of a curve (*Fig. 3*) connecting capacities (expressed in acre-feet) with corresponding river-levels.

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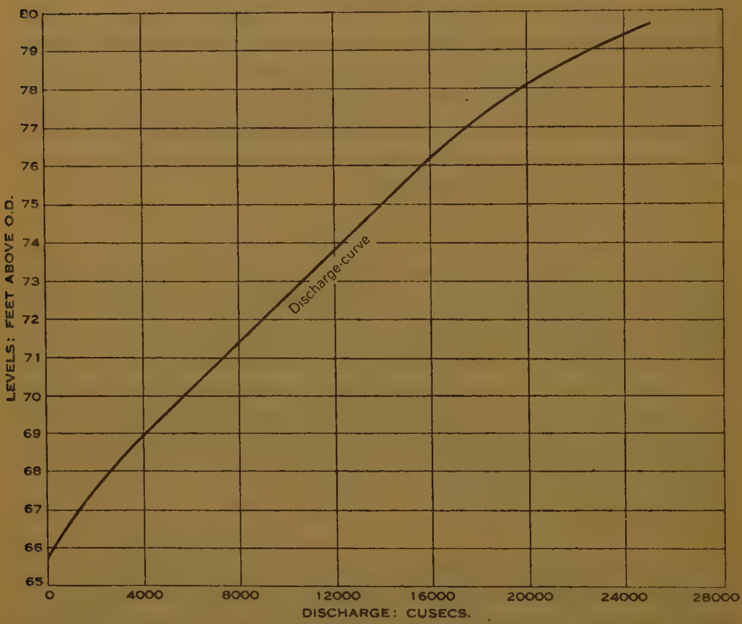
[1] P. 396.

In practice, however, flood-levels over large tracts of land, especially if the flow is obstructed by road-embankments, trees and buildings, are seldom equal at any one moment. A simple method of arriving at the approximate storage-capacity of such an area is by the plotting of what may be termed "depth-contours."

If the peak flood-level at any point is, for example, 82·0 O.D. and the ground-level at this point is 77·0 O.D. the depth of flooding will be 5 feet, and the 5-foot depth-contour will pass through this point.

Fig. 2.



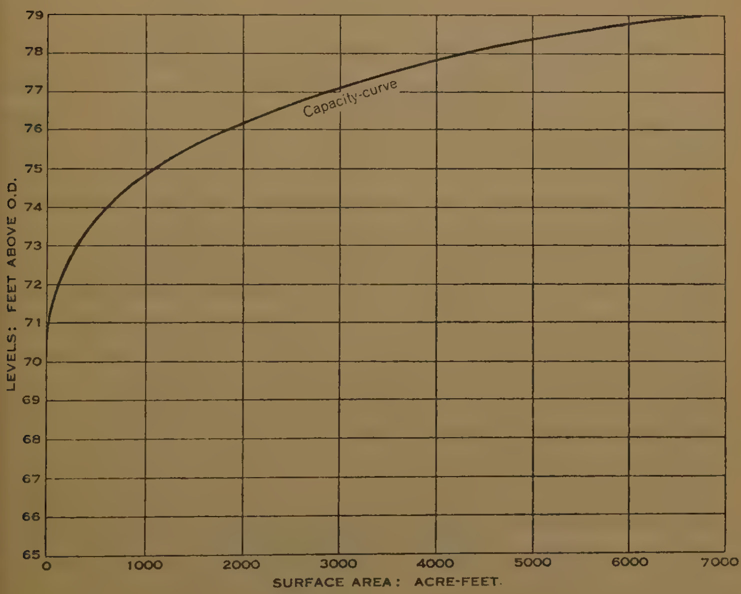
All such points where the depth is 5 feet having been ascertained, the 5-foot depth-contour will be a line, freely drawn, connecting these points. Similarly the contours for all depths from 1 foot upwards may be plotted, the differences at all times being measured between high flood-levels and ground-levels. The zero depth-contour must also be plotted, which will be the boundary between the flooded area and dry land.

For the purposes of this calculation, the assumption is now made that at a flood-level 1 foot below the peak-level, the area flooded would be bounded by the 1-foot depth-contour; at 2 feet below the peak-level by the 2-foot depth-contour, and so on.

By taking out the areas bounded by the depth-contours and

applying Simpson's rule, the volume of flood-water at various depths can now be calculated, and a capacity-curve may be plotted with reference to the river flood-level at a gauging-station immediately below the flooded area. This curve may not be strictly accurate, as the surface-slopes at the lower levels may not quite correspond with the slopes at the peak-level. Again, pockets may exist which are not directly connected with the river and which do not flood until the general flood-level is considerably higher than the ground-level

Fig. 3.



in the pocket. Allowances may have to be made in such cases. However, the curve will be the best that can be obtained in the circumstances, and it will be seen later that an appreciable error in this direction will have little effect on the final result. The exact shape of the hydrograph will be found to be of far greater importance than strict accuracy with regard to the storage-capacity.

Tabulation.

Table II (which, with the Figures and the remaining data given in this Paper, is included by the courtesy of the Engineer to the River Trent Catchment Board) shows the hydrograph for the major flood of May, 1932, at Nottingham; the capacity-curve is that of the area which it is proposed shall be protected by the Nottingham

Flood Protection Scheme. The problem is to ascertain the effect on flood-levels immediately below Nottingham, in an exactly similar flood, should the scheme be carried out.

The method of calculation is as follows:

The hydrograph obtained from an automatic recorder below Trent Bridge has been very accurately plotted to a large scale, allowance having been made for a lag of 1 inch due to the electrical apparatus working in steps of 1 inch at a time. From the plotted hydrograph, hourly readings are tabulated. At 2 a.m. on 23 May, for example, the reading was 77·01 O.D., at 3 a.m. 77·13 O.D. and at 4 a.m. 77·22 O.D., as shown in columns (2) and (3) of Table II.

From the capacity-curve the capacity in the "storage-area" (that is, the land which it is proposed to protect from flooding) is 2,910 acre-feet, at a level of 77·01 O.D., and 3,175 acre-feet at 77·22 O.D., these capacities being entered in column (4). From 2 a.m. to 4 a.m. therefore, the volume of water in the "storage-area" has increased by the difference between these two capacities; that is 265 acre-feet of water have entered the "storage-reservoir." (Column (5).)

The mean flow during this 2-hour period is, therefore, the number of cusecs which will fill 265 acre-feet in 2 hours. One acre-foot is filled by 6·05 cusecs in 2 hours, and therefore the capacity-difference multiplied by 6·05 will give the mean flow, in cusecs, into the area during the 2-hour period. The flow of 1,620 cusecs thus obtained is entered in column (6) opposite the time of 3 a.m., which is approximately the time at which the mean flow will correspond to the actual flow.

At 3 a.m., the river discharge, from the discharge-curve, was 17,940 cusecs, which is entered in column (7). Had the flow into the storage-reservoir been prevented by embankments, the flow in the river at 3 a.m. would have been greater by 1,620 cusecs. By adding 1,620 cusecs to 17,940 cusecs, the flow in the river at 3 a.m. as it would be if the storage-capacity were eliminated is obtained, namely, 19,560 cusecs. (Column (8).)

From the discharge-curve the level in the river for a flow of 19,560 cusecs is 77·85 O.D. (Column (9).) At 3 a.m., therefore, the river-level, instead of being 77·13 O.D. would, without storage, be 77·85 O.D. Similarly, river-levels for all the other uneven hours are obtained. On the falling flood, however, the flows into the area will be negative, that is to say, water will be flowing from the storage-reservoir into the river.

The figures in Column (9) are shown plotted in *Fig. 1* as a dotted line. This curve is the calculated hydrograph as it would be if the storage-capacity of the area, which it is proposed to protect from flooding, were to be eliminated; that is to say, it is the hydrograph

TABLE II.

Date. (1)	Time. (2)	Hydrograph. (3)	Capacity of flooded area: acre-feet. (4)	Capacity-difference: acre-feet. (5)	Mean flow into area: cusecs. (6)	River-discharge: cusecs. (7)	River-discharge without storage: cusecs. (8)	Hydrograph without storage. (9)
May 22	Noon	75·30	1,310					
		75·50		280	1,694	14,980	16,674	76·48
	2 p.m.	75·66	1,590					
		75·84		285	1,725	15,520	17,245	76·78
	4 ,,	75·98	1,875					
		76·12		265	1,602	16,000	17,602	76·96
	6 ,,	76·27	2,140					
		76·39		220	1,331	16,490	17,821	77·08
	8 ,,	76·49	2,350					
		76·56		130	786	16,800	17,586	76·96
	10 ,,	76·62	2,480					
		76·71		210	1,270	17,100	18,370	77·33
	Mnt.	76·80	2,680					
		76·90		230	1,392	17,460	18,852	77·55
	2 a.m.	77·01	2,910					
		77·13		265	1,620	17,940	19,560	77·85
	4 ,,	77·22	3,175					
		77·38		245	1,482	18,480	19,962	77·98
	6 ,,	77·42	3,420					
		77·52		300	1,815	18,780	20,595	78·25
	8 ,,	77·63	3,720					
		77·74		320	1,935	19,300	21,235	78·45
	10 ,,	77·84	4,040					
		77·90		360	2,180	19,700	21,880	78·70
23	Noon	78·07	4,400					
		78·20		400	2,420	20,460	22,880	79·01
	2 p.m.	78·29	4,800					
		78·37		325	1,967	20,940	22,907	79·02
	4 ,,	78·45	5,125					
		78·55		465	2,820	21,440	24,260	79·39
	6 ,,	78·65	5,580					
		78·71		420	2,540	21,920	24,460	79·44
	8 ,,	78·80	6,000					
		78·85		320	1,936	22,350	24,286	79·39
	10 ,,	78·91	6,320					
		78·95		260	1,572	22,680	24,252	79·38
	Mnt.	78·98	6,580					
		79·00		55	333	22,820	23,153	79·09
	2 a.m.	79·00	6,635					
		79·00		– 35	– 208	22,820	22,612	78·93
	4 ,,	78·985	6,600					
		78·965		– 150	– 907	22,720	21,813	78·67
	6 ,,	78·95	6,450					
		78·935		– 150	– 907	22,610	21,703	78·64
	8 ,,	78·90	6,300					
		78·86		– 250	– 1,512	22,380	20,868	78·34
	10 ,,	78·815	6,050					
		78·78		– 230	– 1,392	22,140	20,748	78·30

TABLE II.—*contd.*

Date. (1)	Time. (2)	Hydrograph. (3)	Capacity of flooded area: acre-feet. (4)	Capacity-difference: acre-feet. (5)	Mean flow into area: cusecs. (6)	River-discharge: cusecs. (7)	River-discharge without storage: cusecs. (8)	Hydrograph without storage. (9)
May 24	Noon	78·74	5,820					
		78·70		– 240	– 1,452	21,880	20,428	78·18
	2 p.m.	78·65	5,580					
		78·60		– 230	– 1,392	21,600	20,208	78·11
	4 ,,	78·55	5,350					
		78·495		– 270	– 1,634	21,280	19,646	77·89
	6 ,,	78·43	5,080					
		78·37		– 280	– 1,694	20,940	19,246	77·72
	8 ,,	78·30	4,800					
		78·23		– 230	– 1,392	20,550	19,158	77·68
	10 p.m.	78·17	4,570					
		78·10		– 250	– 1,512	20,200	18,688	77·48
	Mnt.	78·02	4,320					
		77·95		– 220	– 1,331	19,920	18,589	77·43
	2 a.m.	77·88	4,100					
		77·80		– 250	– 1,512	19,440	17,928	77·13
	4 ,,	77·72	3,850					
		77·65		– 230	– 1,392	19,090	17,698	77·02
	6 ,,	77·57	3,620					

of a flood, exactly similar to that of May, 1932, as it would be should the scheme be carried out.

The calculated hydrograph (dotted line) has been superimposed on the actual hydrograph (full line) for the purposes of comparison. It will be seen that the flood consisted of two peaks, the first peak being fairly sharp, the second peak flat and of long duration. On the first peak it will be observed that maximum level actually occurred at 2 a.m. on 24 May, whereas the calculated peak occurs at 7 p.m. on 23 May. This indicates that one of the effects of eliminating storage will be to advance the time of arrival of the peak of the flood by 7 hours. A further effect is the slightly increased flood-level at the peak. The actual flood reached a level of 79·00 O.D., whereas the calculated peak level is 79·40 O.D., an increase of 0·40 feet.

Regarding the second peak, it will be seen that, owing to its flat shape, the differences in level and time of arrival are barely perceptible, while the different behaviour of the two peaks clearly illustrates the argument previously advanced on p. 402.

Practical Results.

It will be observed that the method of calculation assumes that the fluctuations in the flood-level in the storage-reservoir correspond

exactly to the fluctuations in the river-levels. In practice, however, this may not actually occur, as no account has been taken of the loss of head that must take place between the river and the storage-area. This loss of head may only be small, especially at the peak of a flood, but, owing to the difference of level necessary for flow to take place, it is probable that the reservoir does not quite fill, during the rising period, to a level corresponding exactly to the river-level outside the area. The actual flows, therefore, may be rather less than the calculated flows, and therefore the calculated maximum difference in peak level of 0·4 feet may be a little too large. This difference, however, should be correct enough for all practical purposes.

Experimental Verification.

In order to verify the calculated results, experiments have been carried out with the River Trent Catchment Board's model of the Nottingham area. This model is built to a small scale owing to lack of space, and was originally intended for purposes of demonstration only, and not for quantitative measurements. Nevertheless, the model very faithfully reproduces flood-conditions, the levels and flood-outlines corresponding closely to actually-recorded levels.

An attempt was made to reproduce the conditions of a flood similar to that of 1932, the rising and falling flood-hydrograph being obtained by gradually opening and closing a small sluice-valve in accordance with a definite time-scale. The resulting flood-levels were measured by means of a point gauge, firstly with storage as existing, and then, with exactly the same flow conditions, after the storage had been eliminated and a by-pass channel had been cut.

The hydrographs are shown in *Figs. 4* (pp. 410–11), and, while subject to experimental inaccuracies, the results are sufficiently conclusive in demonstrating the time-shift, and a slight increase in flood-level, due to the elimination of storage.

Conclusion.

It has been shown :

(1) That the effect of by-passing on flood-levels below the by-pass is nil.

(2) That the effects of eliminating storage-capacity depend upon :

(*a*) The size of the storage-reservoir in relation to the flow in the river.

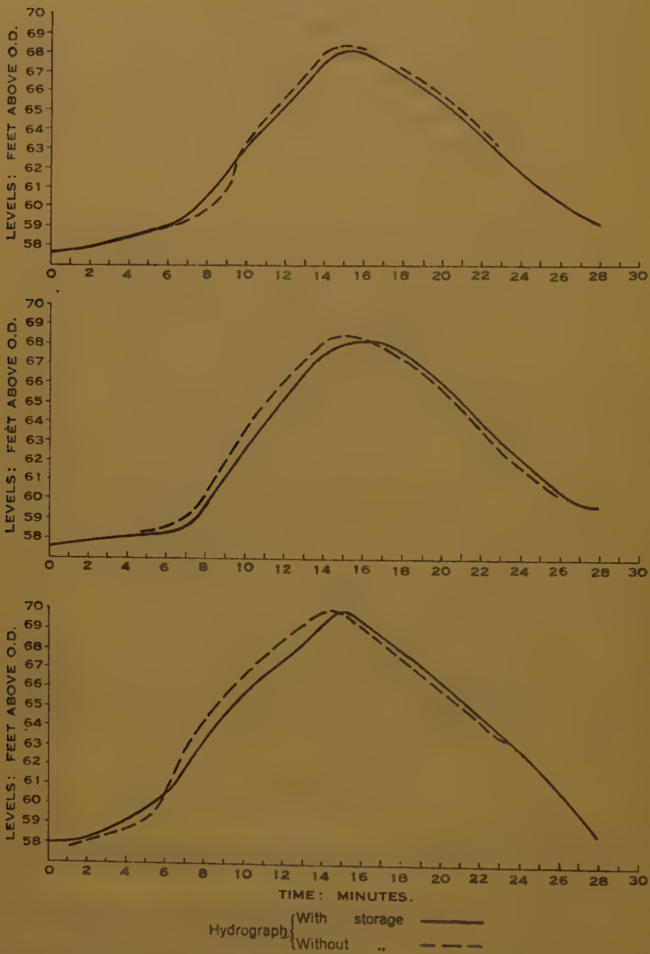
(*b*) The shape of the flood-hydrograph.

In general, the effects will consist of an acceleration of the "flood-wave," and a slight increase of the peak

flood-level in the river below the area from which floods have been excluded.

In the particular case of the Nottingham Flood Protection Scheme, the May, 1932, flood-hydrograph was not only the highest but the

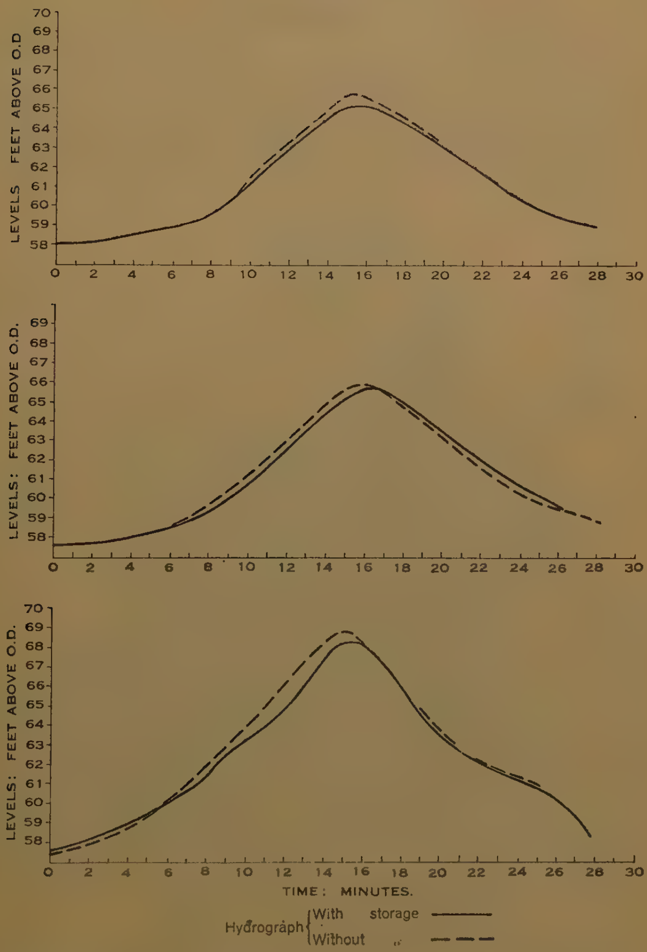
Figs. 4 (a).



sharpest peak of which reliable records are available. An increase of 0·4 foot in flood-level, and a speeding-up of the flood-peak by 7 hours, may, therefore, be regarded as the probable maximum effects, the results of smaller or more prolonged floods being correspondingly less.

In conclusion, the Author wishes to express his sincere thanks to Mr. W. H. Haile, M. Inst. C.E., Engineer to the River Trent Catch-

Figs. 4 (b).



ment Board, for his valuable assistance in editing the Paper, and for permitting the use of actual records.

The Paper is accompanied by two sheets of diagrams, from which the Figures in the text have been prepared.

Discussion.

Mr. Clark. Mr. R. G. Clark showed a number of lantern-slides illustrating the work described in his Paper.

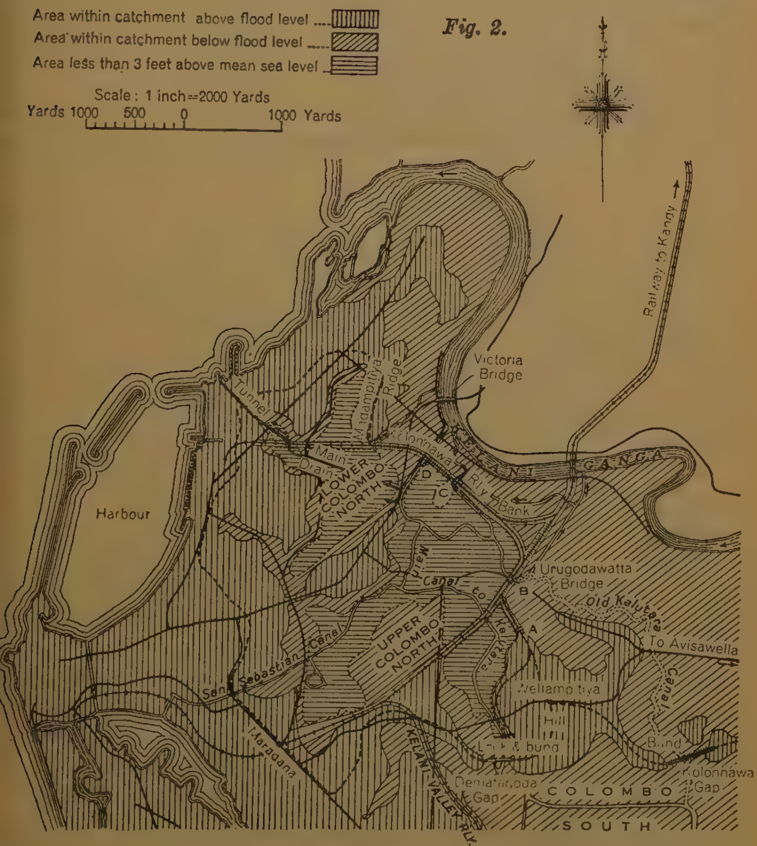
Mr. Hillman. Mr. E. C. Hillman remarked that before his Paper was discussed he would emphasize that it dealt solely with the effect of flood-relief works on flood-levels below such works, and not adjacent to or above such works.

Fig. 1.

An example of a case where the effect of a flood-protection scheme had been to increase the flood-levels over unprotected areas was provided by the Colombo North and South Flood-Protection Schemes in Ceylon. *Fig. 1* was a general map of the two schemes. The first work undertaken was the closing of two gaps in a ridge of hills through which water from the river Kelani had access to the Colombo South basin; the result was so successful that there was a demand

for the scheme to be extended to include the Colombo North area (*Fig.* 2). This was effected by utilizing as a flood bank the railway-embankment shown in the plan, the bridges at points B, C and D, as well as one or two culverts, being blocked for the purpose. The benefits derived from the schemes had never been questioned, and they had enabled the city of Colombo to expand in an easterly Mr. Hillman.

Fig. 2.



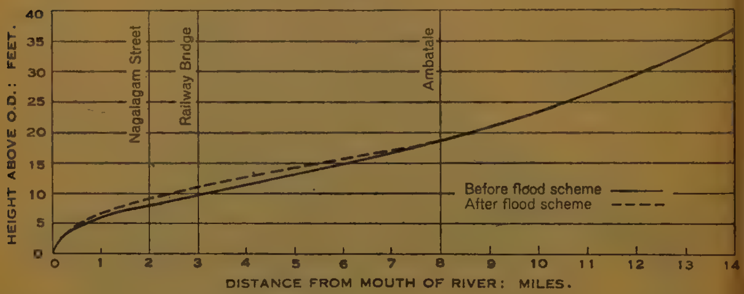
direction, converting hitherto sterile and useless swamps into very valuable property. Those benefits had not, however, been obtained without sacrifice. Owing both to the elimination of the storage-capacity of the protected areas, and also to the "pinching" of the river due to the carrying out of the Colombo North Scheme, flood-levels in the river itself and over unprotected areas were increased.

For some years after the completion of the works all went well, and several floods were successfully resisted. In 1930, however, a

Mr. Hillman. very serious flood was experienced. Owing partly to the increased flood-levels, to meet which insufficient "freeboard" had been allowed, and partly to the fact that the railway-embankment subsided under a load which it had not been designed to resist, overtopping occurred, and the embankment was breached at a point between A and B (*Fig. 2*). The Colombo North area was inundated, but the engineers were fortunately able, after a two-days struggle, to prevent the threatened overtopping and breaching of the smaller of the two Colombo South bunds, by raising the crest-level with rows of earth-filled sandbags.

From a comparison of flood-levels taken before and after the flood-relief schemes, it was found that the effect of the schemes

Fig. 3.



had been to increase the flood-levels over the unprotected areas, as was shown approximately in *Fig. 3*. Owing to that increased flooding, a Government inquiry was instituted, and in order to explain matters the Author wrote a paper for the Engineering Association of Ceylon,[1] his method of calculation being somewhat similar to that used in the present Paper. The results of the calculations were shown in *Fig. 4*. The full line represented the hydrograph as it was after the schemes, and the dotted line the calculated hydrograph of what would have happened prior to the schemes in an exactly similar flood.

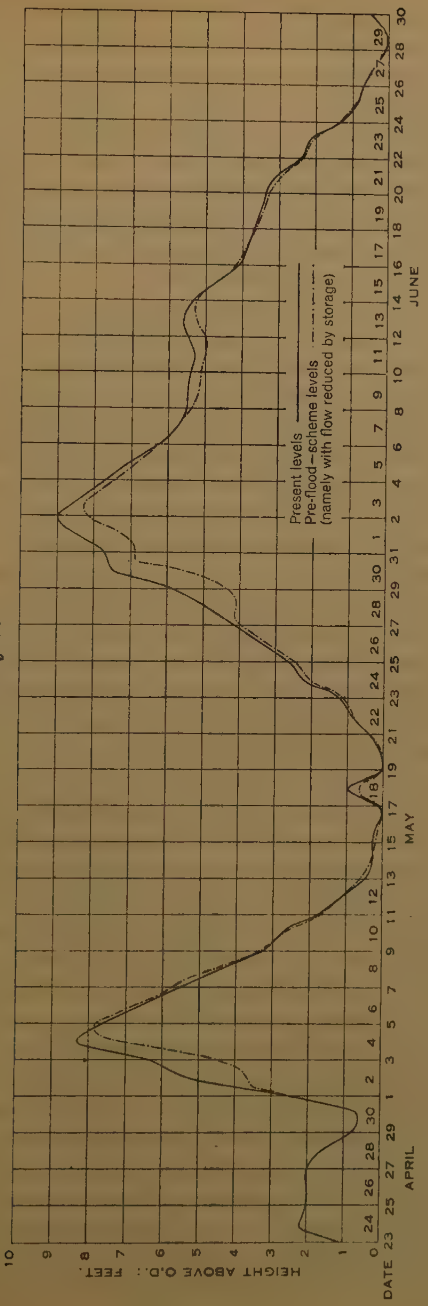
The interesting point was that at a level of about +4·0 O.D. kinks occurred in the calculated hydrographs, but did not occur in the post-flood-scheme hydrographs. Pre-flood scheme hydrographs all showed that characteristic, which was caused by the relief due to the storage-capacity of the areas now protected.

It was only fair to the late Mr. C. C. Harward, C.B.E., Assoc. M. Inst. C.E., who had designed and carried out the schemes, to point

[1] "The Effect of the Colombo Flood Schemes on Unprotected Areas," Trans. Eng. Assoc. Ceylon, Session 1929.

Mr. Hillman.

Fig. 4.



Mr. Hillman. out that he reported that the estimated maximum increase in flood-level over the unprotected areas would be 1 foot 3 inches. To the best of the Author's knowledge there was no evidence that that figure was incorrect.

Mr. Binnie. Mr. W. J. E. Binnie congratulated Mr. Clark on his Paper. As a member of the Ouse Drainage Commission, Mr. Binnie had visited the Middle Level with the other members of the Commission and had had the pleasure of being shown over the works by Mr. Clark; they had been impressed by the excellent way in which all the channels in that area were maintained.

There was very little in the Paper which gave an opening for criticism; the Paper was an informative one, but contained no theories to discuss. There were, however, two points he would mention which might be a little outside the scope of the Paper. In the first place, it would be of interest if Mr. Clark would give the quantity of rain for which he had provided pumping-plant. That was mainly dealt with by the stations in the internal drainage-areas, and he thought that pumping-plant sufficient to rid the ground of about $\frac{1}{4}$ inch of rainfall per day was provided. In the second place, how much had the drainage done for the prosperity of the area affected? He believed that the land was selling at a very high price at the time of the Commissioners' visit, as it was very fertile land which showed the enormous benefits derived from the drainage-system. The pumping-plant had had to be put in owing to the increase in the level of the bed of the river.

A large number of points which were of great interest were raised in Mr. Hillman's Paper. He entirely agreed with Mr. Hillman as to the difficulty of maintaining an enlarged channel. Mr. Hillman had referred to the setting back of the banks instead of enlarging the channel as one of the alternative ways of dealing with the problem, and Mr. Binnie was inclined to think that that was the best method, since in that way there was not so much trouble from silting up. When the method came to be worked out in practice, however, the difficulties of getting the additional land required were generally, or at any rate frequently insuperable.

Dealing with the effect of by-pass-channel flow on flood-levels, Mr. Hillman had stated that the flood-levels below the by-pass would be unaltered, as the discharge was unaltered. If, however, the by-pass had been constructed in order to relieve local flooding, and not merely to cut out a bend, then the peak of the flood-discharge would be increased. That was a practical point which had had to be considered in the case of the river-improvements at Derby, in connection with which Mr. Binnie had been consulted by the Corporation. The water had a big spread when it went over the

bank, and as that storage was lost when the whole of the water was taken down the channel, there was no doubt that it would affect the landowners for a short distance below the works. It was recognized in the arrangements decided upon that it was impossible to prevent any water being temporarily stored without slightly increasing the flood. Mr. Binnie.

On p. 397, Mr. Hillman had said, "An uncontrolled reservoir . . . may operate in such a manner as greatly to augment floods." Mr. Binnie could not understand exactly what was meant by that. Mr. Hillman went on to cite the case of a natural dam of ice or debris being swept away, but that was probably not what was meant by "an uncontrolled reservoir." If one of the reservoir-banks burst, the flood would be on similar lines to those which Mr. Hillman described. In the next paragraph, Mr. Hillman said, "Again, even a properly-constructed reservoir, with spill and sluices, may be practically useless for the purpose of reducing floods if it is not controlled with that end in view; that is to say, it is almost useless if the reservoir is full immediately prior to a heavy storm over the catchment, as in this case there will be little or no extra storage-capacity available at the critical time . . ." He would refer Mr. Hillman to the Floods Report [1] on the effect of the storage-reservoir in reducing the peak-discharge, as shown on Fig. 7, p. 20, of that Report. The reservoir might be full when the flood started, but it rose to a considerable extent above the level of the overflow-sill; when, for instance, it rose 4 feet above the level of the overflow-sill, its spread might be large, and very valuable additional storage might be obtained.

The crux of the whole matter was the ratio between the reservoir-area and the catchment-area. If the reservoir-area was a large proportion—for example, up to 5 per cent.—of the catchment-area, it had a very considerable effect in reducing floods. As an example, if the area of the reservoir was 5 per cent. of the drainage-area, and if it could store water temporarily to a depth of 4 feet over the sill, the peak-discharge would only be 40 per cent. of the flood entering the reservoir. He could not agree, therefore, that a reservoir was not useful in reducing flood-discharge. As Mr. Hillman had pointed out, in order to be of any real benefit to a river the reservoir must have an enormous capacity, and in Table II of the Paper he showed the effect of a particular storage-reservoir in reducing flooding at Nottingham. The total content of that reservoir was 6,022 acre-feet, which was a very small amount to deal with the very heavy

[1] "Interim Report of the Committee on Floods in Relation to Reservoir Practice," Inst. C.E., 1933.

Mr. Binnie. peak discharge of 22,820 cusecs. In the case of the Ouse, Washland was available for storage, capable of holding about 35,000 acre-feet; that area had a spread of 10 square miles and a depth of about 6 feet, and was most valuable in reducing the flood-discharge of the river. The provision of storage on Washland was a valuable expedient in many cases where the necessary land could be obtained.

Mr. Saner. Mr. J. A. SANER congratulated Mr. Clark on the very clear way in which he had described the works dealt with in his Paper, and added that there were one or two points which he would like to mention. Mr. Clark had referred to the shrinkage of the fenland; presumably the land shrunk as a whole, and not only between the ditches. If that were so, the great difficulty of collecting the water would be easily understood, whilst the works would last for only a short time.

With regard to the alteration of low water and the accumulation of mud at the bottom of the estuary and mouth of the Ouse, the question of dredging the estuary must have been considered, but an inspection of the Ordnance sheet for a few minutes would show that the dredging required in the estuary of the Wash would be very expensive, whilst it would be very uncertain that the channel would stay for long in the position dredged.

Mr. Clark was probably right in placing his pumps so that in discharging they would help to remove the mud in front of the sluices; he had also been very wise in specifying helical teeth for the gear-wheels, so that they were not only silent but were also free from vibration, because he must have had very great difficulty in getting everything solid with such a treacherous bottom.

There was, however, one thing which Mr. Clark might have done. It was stated in the Paper that the cost of electricity would have been more than the cost of the diesel engines, but it remained to be seen whether that was so or not; with electricity Mr. Clark could have had automatic control and could perhaps have saved some of the expense of having someone present the whole time to look after the engines.

The apron on the river Ouse side was rather thin, and he would have preferred to have had something a little heavier. An inspection of the bore-holes shown in the Paper showed that the ground appeared to be more or less liquid, and if the piles had been at the end of the sheeting it would have helped to prevent any undermining as the water went over the end. He had had a good deal of experience of the action of water from sluices, and he thought that although the concrete might be reinforced it would bend, and would perhaps disintegrate.

He was very interested in the information given with regard to Mr. Saner. e Danzig piles, because it agreed with his own experience that on any occasions piles which had been in position for 70 or 80 years ere in very good condition. They were so well preserved, in fact, at on several occasions he had advised the use of timber piles, pecially when they were tongued and grooved.

With regard to the second Paper, Mr. Hillman had put forward a very concise form essential factors of the matters to be con- dered in connection with flood-discharges; he had also given some ry useful and interesting information with regard to the river rent, which was, however, unfortunately limited to so short a riod as 11 days. Mr. Saner was quite aware of the work involved producing reliable data over long periods, because in 1905–06 had obtained approximate figures for the river Weaver for a period 12 months. The Weaver had a catchment-area of about 540 uare miles, and the computed amount of rainfall on the basin d varied from 26,212,000 cubic yards in December, 1905, to 5,148,000 cubic yards in the following month, so that the discharge the river had been nearly eight times as much in January as in ecember. In August, 1905, the fall had been nearly 192,000,000 bic yards, and it had been possible to account for only 1·7 per cent. the water; in December of the same year, however, 81·29 per nt. had been accounted for. Those figures showed the very eat difference in the conditions during winter and summer; it s very important to consider both sides of the question and not concentrate merely on the latest phase of the weather in the er-changing climate of Great Britain.

It was evident, as had been pointed out by the Committee on oods in their recently-published Report,[1] that many more data ere required, for although there were numerous records of rainfall, ich in some cases went back for 70 or 80 years, or even more, ere were very few records of the relative discharge of the rivers d streams following such rainfall, or of the lag in time—a very portant matter—between the fall of the rain and the arrival of e flood-water at any given point in the valley. That period of ne could be obtained only by synchronizing the rain-gauges and gauges on the rivers, either by accurate clocks or by electrical ans.

He might give an example of the necessity for such gauges by erring again to the river Weaver. The main line of the river lay tirely on the sands and gravel overlying the Keuper marls, and flow was much slower than its most important tributary, the

[1] *Loc. cit.*

Mr. Saner.

river Dane, which rose at Axe Edge in the Pennines and passed fo a third of its length over millstone grit. The Dane came down in a torrential flood. As a guide to the weir-keepers on the river, they used to be told to expect the maximum height of the flood about 14 hours after the rain had ceased falling on the Weaver valley. There were, unfortunately, no really accurate figures available, but that period had generally been assumed.

Mr. Hillman had mentioned in the Paper the data that were required, namely, the amount of rainfall and the discharge of the river. If continuous readings were taken at each place, and the records then superimposed, they would determine at once the time taken by the flood-water to flow down the river. After that the problem for the Catchment Boards was very serious; they had to take into account not only the suburban and urban requirements, but also the agricultural needs, and in some cases the domestic supplies. Mr. Hillman pointed out, by reference to the river Trent, that it was not possible to provide reservoirs of sufficient size to control all the flood-water during the really wet season, but that did not mean that reservoirs would not be useful in regulating the river in times of moderate rainfall and drought; the latter became an important matter in the summer. Generally speaking, floods occurred only at certain periods during the year.

Much was owed to the floods in providing the rich pasture-lands where the high-standard breeds of cattle were fed; flood-water which lay on the land for a few days certainly did no harm and was often beneficial, as it filled up the underground reservoirs from which the springs were derived. Where a flood did cause damage was where houses had been built in places where they should never have been built, and where no precautions had been taken by embanking or pumping or in any other way. It might be said that the lower river could be improved, but that involved the very important question of tides, and interference with the channels o a river was often undesirable. Every case had to be studied on it merits, but he thought that a combination of reservoirs and longitudinal embankments, or embankments placed in certain specially selected places, would do very much towards equalizing an controlling the rivers, both as regards floods and during periods o drought.

Mr. Silcock.

Mr. E. J. Silcock congratulated Mr. Clark upon the completio of a most difficult piece of engineering work. The basis on whic Mr. Clark had determined the capacity of the pumping plant wa not stated in the Paper, but from the data given it appeared that th combined capacity of the three pumping-units was equivalent to run-off of ¼ inch of rain in 24 hours on the area drained. In adoptin

ıat basis Mr. Clark followed the practice of the late Mr. W. H. Mr. Silcock.
7heeler, M. Inst. C.E., who was regarded as the doyen of fen-rainage engineers. That basis had proved, in many cases which ad come within Mr. Silcock's knowledge, to be a safe provision to ıake for a fen-drainage district of the type in question.

It would increase the value of the Paper if some information could e added to describe the effect of the works upon the drainage in ıe Middle Level. The wet season in the autumn of 1935 and the eginning of 1936 had provided ample opportunities for observing ıe results obtained by the new works. It would be interesting to now whether, during the past autumn, the pumping-plant had been ıpable of dealing with the run-off, and also whether the Main Drain ad sufficient capacity to keep the pumps running continuously ı that connection it would be useful to know the surface-gradient ı the Main Drain when the pumps were working to capacity and umping water to the lowest practicable level, as that seemed to ave a very important bearing upon the question as to whether or ot the pumping-station was placed on the most advantageous site r draining the district.

The Author had stated that the new main drain was cut through 2 miles of marshland from St. Germans to Upwell. It was stated ıat the farthest point to be drained in the fenland was 30 miles way from the sluice, and that the peat there was still shrinking. ery similar conditions, but on a smaller scale, were experienced in drainage-district on the eastern side of the river Ouse in the fen-rea in Norfolk drained by Sam's Cut. That drain, which was about miles in length, had been originally constructed as a gravitation-rain, and discharged by gravity into the river Ouse about 10 miles bove St. Germans sluice. The drain continued to function for ome years, but it was found that, owing to the shrinkage of the eat, natural drainage was insufficient, and a pump was erected the outfall into the river Ouse in a position corresponding to ıat adopted for the Middle Level by Mr. Clark.

That pumping-plant had been in operation for some years when, wing to further subsidence of the peat, it was found necessary to rovide an additional pumping-plant at a distance of 4 miles up the rain from the point of discharge into the Ouse. In course of time ıat plant became ineffective by reason of the continual settlement the fens, and within the last few years it had been necessary to ake a further alteration in the drainage of that cut, which had now een diverted to a new pumping-plant that delivered the water to the river Wissey.

The experience gained in that case, which was no doubt well known Mr. Clark, suggested that possibly the most effective plan of

Mr. Silcock. improving the drainage of the Middle Level district would hav been to have erected the pumping-plant near the upper end of th new Middle Level drain, in the neighbourhood of Upwell.

By that means the pumps would have been 10 miles nearer t the extreme point to be drained, and would have delivered int the existing drain, which was of such a depth below ground-level tha it would form an effective outfall to the river; that scheme migh have involved the construction of flood-banks along a part at leas of the course of that drain, but would probably have been less costl than dredging the existing drain to afford effective drainage to th new pumps.

No doubt that solution of the problem had received consideratio by Mr. Clark before he put forward the scheme which had bee carried out, but it would add to the value of his Paper if he would in his reply, discuss the reasons which led to the choice of the selecte site.

Mr. Haile. Mr. W. H. Haile said that, as Mr. Hillman had been kind enoug to refer to him in his Paper, he was glad to have the present oppor tunity of making a few supplementary remarks.

When the Royal Commission on Land Drainage drew up it excellent Report in 1927, it expressed the opinion that "If drainag is to be effective the first requirement is to clear the main strean of the river, beginning with the outfall and working up toward the source." That was a counsel of perfection, however, whicl could not always be carried out.

The River Trent Catchment Board, which had only been i existence for $4\frac{1}{2}$ years, had developed a policy of works to embrac a comprehensive scheme, but it was realized that work should firs be carried out where the greatest damage was done, providing ther was no resultant damage inflicted on the areas below such works In May, 1932, very bad flooding had occurred in the whole of th Trent valley, and West Bridgford and parts of Nottingham ha suffered severely. The position of Nottingham was shown in *Fig. 5* which showed that all the main tributaries of the Trent area dis charged into the Trent above Nottingham, whilst from Nottinghan down to the outfall into the Humber there were only two tributarie of any size discharging into the river. It would also be seen tha there were no towns of any size between Nottingham and the moutl of the river with the exception of Newark and Gainsborough, whicl were smallish towns each of about 18,000 inhabitants. Both of thos towns were largely unaffected by floods, because they happened to b clear of the flood-water level; to the west of the Trent area, howeve there were the Potteries with the large industrial areas, includin Birmingham, to the south-west.

The point he desired to make was that between Nottingham and Mr. Haile. he outfall of the river, with the exception of the two small towns e had mentioned, the river flowed through principally grassland nd rural districts. If those concerned were to start their improveent-scheme at the mouth of the river and to work up-stream, they ould have to carry out a lot of work in the form of setting back ood-embankments right up to Nottingham itself. Taking into conderation the time consumed in acquiring wayleaves and lands, it

Fig. 5.

River Trent Catchment Area.

ould be many years before Nottingham was reached, where onsiderable damage had been done in the urban district of West ridgford by the floods of 1932. The Nottingham engineers had ad to satisfy the Board and the riparian owners below that any

Mr. Haile. works carried out in Nottingham would not be detrimental to th lands below. That problem had been the genesis of the Paper.

He would like to point out the difference between flooding in an urban area and flooding on grasslands, to which Mr. Saner had referred. The damage done by flooding in a built-up area was so great that, if possible, protective works for such areas should be carried out before grasslands were protected, since a great deal of good was often done to grasslands by flood-water.

Mr. Borer. Mr. OSCAR BORER, having in mind the many disasters which had occurred in the Fen country, thought that Mr. Clark was to be congratulated on the successful completion of St. Germans pumping station. Mr. Clark had had experience of two failures, one at Denver Sluice and one in his own area, and it was therefore not surprising that so many piles had had to be driven underneath the pumping-station.

The capacity of the pumping-station had been referred to by Mr. Silcock, and he would mention that the pumps had a total capacity of 1,500 cubic feet per second, thus giving a run-off from the Middle Level area of ¼ inch in 24 hours. It had to be remembered, however, that those pumps were working against varying tidal conditions, and he did not think it would be possible to evacuate that quantity of water throughout the period of 24 hours.

Mr. Clark had wisely provided for the installing of a fourth pump, but Mr. Borer hoped it would never become necessary for that pump to be put in, because it would accentuate the problem of the disposal of the water, for which the Ouse Catchment Board were responsible.

During the course of the flood on 4 February, 1936, attempts had been made to gauge the water in the river Ouse under flood-conditions. The discharge at Welmore lake sluice was about 6,000 cubic feet per second. Denver, which was about 9 miles above St. Germans, had been gauged as discharging about 3,000 cubic feet per second, while the Hundred Foot river was passing 1,800 cubic feet per second, and the St. Germans pumps were, fortunately, only adding 1,000 cubic feet per second. He had had an automatic gauge set up at a point near St. Germans to see if it was possible to ascertain the effect of that additional water going into the river Ouse. At about low tide on 4 February the Middle Level pumps had had to be closed down for an hour in order to have their screens cleaned, and the automatic gauge had shown a sudden fall of a foot. It was curious that it should have done so, and he could not be certain about the matter as the temperature was then below freezing point; the gauge might have become caught up, and then have fallen, owing to the sudden stopping of the pumps. He had had tidal curves taken on that date from the open sea through the whole of the tidal Ouse, but he could not get any

nfirmation of them; he was afraid that the man who was re- Mr. Borer. onsible for taking the gauge-readings at St. Germans must have ken a few readings, assumed that everything was all right, and must en have left, because the curves showed a series of irregularities hich could not be explained.

The great problem which still faced the Middle Level was the atter of shrinkage. The figure given by Mr. Clark of ½ inch a ear was a conservative estimate, although it was one which r. Borer used. He was loth to think that the Fen areas were ttling faster than that, but if reference were made to the cast-iron llar which had been erected at Denton Fen at the top end of the iddle Level, it would be realized that in 1848 the top of that llar had been 5 feet 6 inches above Ordnance Datum and that e land had shrunk 8 feet in the next 27 years. Since then it had llen 2 feet 6 inches, which was an average shrinkage of ½ inch a ear. It should be remembered, however, that Denton Fen had een allowed to revert to its former state, so that it was not ıbjected to full drainage-conditions.

The effect of St. Germans pumping-station would be that the umps of the Middle Level Internal Boards would be able to pump ore easily, and, as a great many of those pumps were of inadequate ıpacity, it meant that the Middle Level generally would be better rained. The inevitable result of improved drainage in the Fen area as a quicker wastage of the land. The drop was not entirely a ırinkage but was partly due to the blowing away of the peat under e dry conditions.

Mr. Clark had not emphasized his problem seriously enough. he Middle Level was generally at about Ordnance Datum, and that as just about the level to which the tide fell in the river under ood-conditions. That level was maintained for a distance of 5 miles, from March to Ramsay. From March down to St. Germans umping-station was another 15 miles, and the water had therefore be got down by creating an hydraulic gradient artificially. The roblem in time to come was whether St. Germans pumping-station was the correct place. St. Germans pumping-station had gained about feet gross fall after being moved down the river about 9 miles.

Much peat existed at the top end of the Middle Level, but there ere also harder strata which had not settled, and the Middle Level nerally did not settle evenly. The position of the pumping-stations ıd had to be altered from time to time, and drains had had to be ıt in different directions.

The low tide at Denver during the flood on 4 February, 1936, ıly fell to 9 feet O.D. instead of to 4 feet 6 inches O.D., while St. Germans the level was at Ordnance Datum instead of being

Mr. Borer. about — 3 O.D. If, therefore, much more water were brough in from the Middle Level it would mean that all the tidal curve would be raised. Although St. Germans was almost at the head o the outfall, he could not decide how far St. Germans pumping-statio was going to affect the general conditions on the river Ouse.

Mr. Griffiths. Mr. G. J. Griffiths offered Mr. Clark his congratulations o having obtained a stable foundation for his pumping-station. H would ask Mr. Clark whether he had found that the bottom hac risen as the piles had gone down. That had occurred in simila formations, and he would like a little guidance on that point.

With regard to Mr. Hillman's Paper, he believed that it woulc be a very useful guide to those who had similar problems to face With regard to channel-improvement or by-passing with the objec of reducing flood-levels locally, wherever it was possible to trea the river as a whole it was desirable that the work should com mence at the lower end, and should work up-stream, even if, owin to financial considerations, that method involved dealing with th problem by instalments. That factor was not always appreciatec by those situated some distance from the source, who were ofte anxious for priority in the matter of flood-relief measures. In an case, as Mr. Hillman had suggested, quantitative data would hav to be obtained before a sound scheme could be prepared.

With regard to embankment-systems which excluded flood water from certain areas, such systems could often be usefull employed in agricultural districts in the natural flood-channel of th valley where there were not many tributaries, and where a certai amount of excess flow could be accommodated. That, in his view would be classed as an uncontrolled reservoir, or spill-over, an would in certain cases be of considerable value.

He noticed that Mr. Hillman was of the opinion that, generall speaking, for English rivers the ratio of high-flood flow to "bank full" discharge might be taken as approximately 3 to 1; for th river Thames, the ratio was nearer 2 to 1, as a discharge of 8,32 cusecs was the "bank-full" flow, whereas an average high-floo flow might be taken as about 16,650 cusecs. The peak discharge at Teddington of the five highest floods in recent years were a given in the Table on p. 427.

With regard to uncontrolled reservoirs, he did not know whethe he quite understood the Paper, but he looked upon them as bein a form of spill-over which, in some cases, was extraordinarily usef and which could be made by means of embankments. In the tida flood of the river Thames in 1928, the presence of spill-overs ha affected the hydraulic gradient to a very large extent.

It was interesting to see that an estimate had been given of th

ize of an hypothetical reservoir for the purpose of regulating the low of the river Trent in a flood similar to that of May, 1932. A eservoir having a capacity equivalent to 207 square miles of country looded to a depth of 1 foot, or to 69 square miles flooded to an verage depth of 3 feet, would be entailed, and he agreed with Ir. Hillman that such a reservoir was impracticable. Mr. Griffiths.

Mr. Hillman had dealt with the manner in which a flood-relief eservoir might be controlled, and had given as an example the low of the river Trent for a flood lasting 11 days. By way of omparison Mr. Griffiths thought it might be of interest if he gave few facts relating to the flood-flows in the Thames. From 9 November, 1929, to 6 February, 1930, the river Thames was owing "bank-high" or over, with the exception of 8 days, when he flow fell temporarily below 4,500 million gallons per day, or ,325 cusecs; the lowest flow was 3,643 million gallons per day, or

Year.	Discharge per day: million gallons.	Flow: cusecs.
1926	7,031	13,007
1928	9,999	18,498
1929	10,489	19,404
1933	9,095	16,825
1936	9,000	16,650
	Average 9,123	16,878

,739 cusecs. The whole period comprised 70 days, and the peak ow was 10,489 million gallons daily, or 19,404 cusecs.

The idea of controlling the high-flood flow of a river by means of iverting into one or more reservoirs either the whole or a proportion f the flow over and above an amount that could be carried by the ver-channel itself, without overflow, was not new, and should rtainly not be lost sight of when any scheme for flood-amelioration a river-valley was being considered, but it would be found, in e majority of cases, that the financial aspect of the question ndered the scheme impracticable. In the reservoir described in e Paper the excess discharge for the 11-day period was computed about 36,000 million gallons, and it would be of great interest if r. Hillman could give any particulars of the estimated cost of the nstruction of such a reservoir. If it were suggested that the servoir could be used for the dual purpose of storage for water-pply and flood-relief, then he would like to have some details as to st per million gallons of storage.

He ventured to think that only in very rare instances could

Mr. Griffiths. reservoirs be used for the dual purpose. He would like to emphasize that aspect of the question, because it was sometimes considered practicable to use them for both purposes. Such a reservoir would have to be empty immediately prior to a period of high flow, and, as it was impossible to forecast with any accuracy when that would occur, the reservoir would not be very satisfactory from the point of view of water-storage.

In connection with flood-relief in smaller catchments, the quantity which would have to be impounded and stored during a flood-period for use as subsequent water-supply might be an important factor in bringing about a considerable reduction in the flood-flow, and that point of view should not be lost sight of by Catchment Boards. In general the two questions should be considered together, but for catchments such as the Trent, with flood-volumes of the magnitude under discussion, the quantity which could be economically stored was, as a rule, infinitesimal as compared with the flood-volume which had to be dealt with. Further, he was certain that once the water had been pumped to store it would not be readily relinquished for the benefit of the river.

Mr. Hill. Mr. David G. Hill remarked that the excavation for the foundation of the sluices and pumping-station at St. Germans was commenced on the north side. When the level was reached where the soft clay and peat met there was a great tendency for slips to occur, as Mr. Clark had pointed out in the case of the temporary downstream dam. After consultation on the site, and while the site was being enclosed with Larssen steel piling, it was considered advisable to drive an additional row of steel piling across the site, about three-quarters of the length of the row from the north side. That enabled the excavation to be taken out over three-quarters of the area and filled in with mass-concrete round the concrete piles, thereby ensuring a balancing effect on that section of the foundation and also providing a toe to strut against while the remaining quarter of the area was being excavated. That last portion of the excavation was considered to be the danger-point of the work, there being a margin of only 60 feet between it and the tidal outlet of the old sluice, but the method adopted served to avoid any serious slips. The Kimmeridge clay on which the work was founded had, so far as was known, never before been exposed in that district. It was so tough and compact that pneumatic clay-diggers were employed, as excavating by pick and shovel was difficult and laborious. Mr. Clark had mentioned that the concrete piles were lifted by the driving of the raking piles; the additional row of steel piling was also lifted about 12 inches in one place, due undoubtedly to the driving of the concrete piles through such dense material. A

umber of the concrete piles which were lifted were tested, and were found to be as sound as when originally driven. Out of the hirteen hundred and eighty-nine concrete piles driven, only fifteen pile-heads were damaged, owing to the great care exercised in making nd driving the piles; the main bars of the piles were cut to one evel with a hacksaw, thereby ensuring an even blow on all the main bars during driving, and a sound packing of Oregon pine $3\frac{1}{2}$ inches hick, in place of sawdust or bags, was maintained in the helmet. Mr. Hill.

During the period of excavation, a close examination of the various peats, silts, and clays at the site was made by Messrs. H. and M. E. Godwin, of the School of Botany, Cambridge, and a report [1] on the geology was made by Mr. F. H. Edmunds, which should be of considerable interest to engineers carrying out work in deep foundations n that district.

Mr. Clark had mentioned that the lower sections of the pumps nd sluice-valves were erected on the concrete raft and not, as was he usual practice, after the engine-houses were erected, which would have been practically impossible, owing to the bulky and heavy sections to be handled. Those lower parts of the pumps were placed in position by the derrick-cranes which had handled the xcavation and concrete-placing; they were then encased in concrete ip to engine-house floor-level.

The Henderson drag-scraper, which was used for the excavation of he old channel, proved to be an extremely cheap and efficient machine for dealing with the excavation. The cost per cubic ard, including excavating and tipping to spoil at an average distance f about 150 yards away, was $8\frac{1}{4}d.$; that figure included all costs or labour, plant, and power, as well as the complete writing-off of he cost of the scraper.

Mr. W. M. GRIFFITH congratulated Mr. Clark on his achievement. When the scheme had first been mooted he believed that some ngineers had taken a different view from that of Mr. Clark, but Mr. Clark had had the courage of his convictions, and Mr. Griffith hought that events now showed that Mr. Clark had been fully ustified in those convictions. Mr. Griffith.

In his Paper Mr. Clark had mentioned that part of the trouble f the Middle Fen drainage which had given rise to the introduction f pumping instead of a gravity outfall was due to the bad state of he river Ouse, and he had added that in 1880 the drainage had been etter than it was in 1912, and that further difficulties had developed n 1916, 1926, and 1928. Mr. Griffith had recently made a study f the rise in the bed of the Ouse, and had found that there was no

[1] "Pollen Analyses of Fenland Peats at St. Germans near King's Lynn," *Geological Magazine*, volume lxx, April, 1933.

Mr. Griffith.

evidence of any serious rise before the year 1912. From 1913 up to the year 1922, when Denver sluice (which evacuated the waters of the South Level rivers) was remodelled and enlarged, there was a very sharp rise in the level of the river-bed, commencing at the sea and travelling up the river. So rapid had it been that it had given rise to the theory that in a very short time the Ouse might cease to function as a satisfactory drainage outlet for the Fen areas.[1] This had led to several large schemes being prepared by different engineers to remedy the evil, and Mr. Griffith thought that it might be of interest if he gave the result of his study of the river-bed. He had found evidence to show that the sudden rise in the river-bed was not due to the gradual silting-up of the bed of the Wash, into which the river discharged, but that it was due to gaps which had occurred in the training walls; the latter were at the mouth of the river, and extended for about a mile into the Wash. They had been built in 1852 to confine the passage at the mouth of the river, in order to assist in the maintenance of the channel into the Wash, as well as to assist in land-reclamation. No proper maintenance-work had been done on those training walls, and they had begun to sink and fail.

There was evidence to show that from 1913 the main channel at the seaward end of the training walls on the east side had commenced to silt up, and a false channel had formed at the back of the west wall. That showed that, due to the settlement and gaps, the outfall had ceased to function in the way it had been functioning, namely, in being confined to the main channel by the training walls and in building up silt-banks behind those walls. Accumulations of silt formed in the past behind the walls were being washed into the channel and were drifted up the tidal river by the tidal action, thus raising the bed and affecting the Middle Level outfall. It had taken 6 years for that rise in the bed to work up to Denver, a distance of 16 miles. A rise in drainage level of from 1 to 2 feet had occurred at the Middle Level outfall.

The rapid rise in the bed had been finally stopped with the remodelling of Denver sluice in 1922. That remodelling consisted of remodelling the sluice-gates and opening a new eye, which was an additional sluice of 34 feet span. The action of the remodelling of Denver sluice in stopping the rise in the river bed had, in Mr. Griffith's opinion, been two-fold:

(1) It had given a bigger capacity for discharge of the river behind, and there was less wire-drawing at the sluice.

(2) The new span or eye was too wide to be fitted with tidal-flap

[1] Minutes of Evidence, Ouse Drainage Bill, 1927, p. 82.

oors or other non-returning gates, as were the other spans, and was Mr. Griffith.
tted with a Stoney roller-gate, and in the remodelling the other pans were also fitted with Stoney roller-gates in addition to their dal gates.

In consequence, the Denver sluice-gates were not now always pened on an even water-level on both sides, as in the case of tidal oors, and there was a certain amount of scouring by the sluice; though scouring power was now available in the new sluice-gates Denver and Welmore lake, very little had yet been done to utilize e full scouring effects of those sluices.

The training walls had now been repaired and raised, and in Mr. riffith's opinion the bed of the river would now tend gradually to nk to its old level. Mr. Griffith considered that that action could e greatly accelerated by scientifically working the sluices at Denver d Welmore lake. He did not wish to imply that that would alter r. Clark's problem. The real trouble, as he understood it, was the eady settlement of the Fen areas, and the stage had been reached hen it was necessary to adopt an entirely new procedure, namely, pump the Middle Level discharge under high-flood conditions stead of trying to gravitate the discharge.

Since the works described in Mr. Clark's Paper had been completed e big flood had occurred, and he would be very much obliged to r. Clark if he would give some information about his pumping-stem during that flood. Would it be feasible to design a plant the kind described which need not take the full maximum outfall a river? That was to say, could it be combined practically with rtial gravitation, under high-flood conditions, or would it have to designed to deal with the whole volume of flood-water? In his inion he thought it would have to be designed to deal with the hole maximum flood-discharge.

Mr. Arthur Sykes offered his congratulations to Mr. Clark for the Mr. Sykes.
ecution of the work. The part in which he was particularly terested was the reducing-gear connecting the engines to the imps, of which details had been given in the Paper. The problem d not been regarded as a particularly difficult one, as the turning oment was comparatively uniform with a centrifugal pump on e side and a multiple-cylinder engine on the other. The gear-tio of 3-to-1 was comparatively small, and the efficiency was 98 per nt.

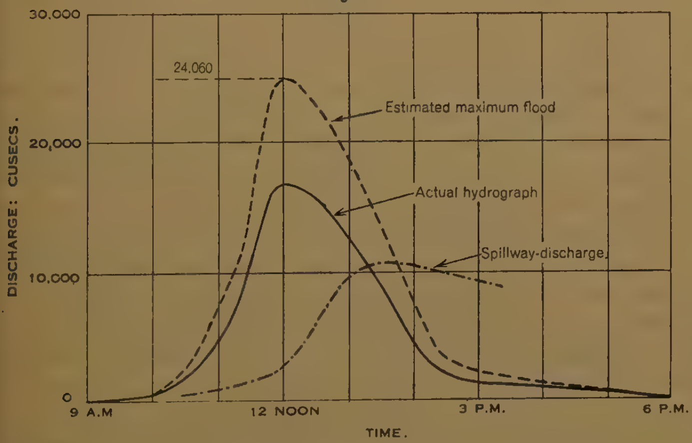
An interesting point had arisen shortly after the units had been it to work. The wheels had been constructed with steel rims shrunk to cast-iron centres. After they had been working for some time was noticed that the rims were creeping out of position. Many ars ago it had been the regular practice in the shrinkage of steel

Mr. Sykes. rims to fix them in position with pins on the line of the joint, but later it had been thought by many that if the pins could be omitted it would avoid interference with the rim section, and would therefore give a greater factor of safety against breakage. It had also been considered that the gripping force was so large that the rim could not possibly slip; if the rims gripped uniformly all round then the force required to move them was very large. In the gears in question the shrinkage-allowance on the wheel, which was about 45 inches in diameter, was about 0·037 inch; the force applied, however, was not uniform all around, but was applied at one point only, namely, where the wheel made contact with its pinion. If a bunch of papers with a rubber band placed round them were taken, and a finger pushed on the band, it would be found that the band would gradually creep round, due to its being compressed slightly on one side of the point of application of the force, and extended a little on the other side. It had not been appreciated, however, that the same thing might occur in a steel rim, which was also flexible, although in a much smaller degree. The rims had crept sideways by the action of the helical teeth, in one case to the extent of about 1¼ inch. Slipping had occurred in one set only, in which the direction of rotation was such that the thrust on the helices was outwards, each helix having been cut in a separate rim-forging. No movement had taken place on the other wheels, and it was clear that the resistance to circumferential slip was considerably greater than the resistance to side-slip, as the axial load was considerably less than the circumferential load. The angle of the teeth was 30 degrees. Fortunately, the difficulty was easily and quickly overcome by re-shrinking and pinning. It had been possible, however, from data which had been derived from the pumping-station and from another similar instance, to formulate rules whereby such an occurrence could be avoided. It depended on the relation between the thickness and the diameter of the rim.

Mr. Braine. Mr. C. D. C. Braine said that the effect of a reservoir upon flood-levels could be very marked, owing to the balancing of the peak flow. In the case of the Bon Accord dam, across the Aapies river, which had been designed and built by his father, the late Mr. C. D. H. Braine, M. Inst. C.E., the waste-weir had been designed to deal with a flood 50 per cent. greater than the greatest hitherto recorded there. The maximum depth of water in the dam was about 45 feet, its capacity at full supply-level was about 400 million cubic feet, and the area submerged at waste-weir level was 614 acres. The catchment-area was 121 square miles, and included the city of Pretoria. The hydrograph of the greatest recorded flood, that of the estimated "highest flood," and the corresponding discharges

ver the spillway were shown in *Fig. 6*. It would be seen that, **Mr. Braine.**
vith the dam full at the start, the maximum discharge over the pillway was only 30 per cent. of the peak discharge of the river. The actual flood-peak had been 16,040 cusecs, and adding 50 per ent. to it, the peak at the dam site had been taken as 24,060 cusecs. By allowing for the balancing effect of the dam, the waste-weir had een reduced in length from 1,083 feet to 416 feet, and the resulting naximum flood downstream had been calculated to be only 9,800 usecs. With regard to that dam, it was perhaps worth recording that ts waste-weir had been designed before Mr. H. H. Dare's Paper on he Burrinjuck spillways [1] had been published, and that the late Mr. C. D. H. Braine had been disappointed to find that the use of he balancing effect of a dam to reduce the spillway, which he had

Fig. 6.



nagined to be an entirely original idea, had already been developed y others.

Mr. Hillman had suggested that a reservoir should impound all the ood-water of the greatest flood above the maximum that the river vould carry, and showed that in the case of the Nottingham Flood-Protection Scheme that was impracticable. In such a case, surely vorks should be designed to eliminate the frequent small floods, even hough they only reduced the great floods that occurred once in a ecade. At Bon Accord the flood-peak, although short, had been ery high and quite typical of the country. Although the dam was omparatively small, its effect on floods was marked. If Mr. Hillman vould consider the value of that balancing he would probably find

[1] Minutes of Proceedings Inst. C.E., vol. ccxiv (1921–22), Part II., p. 333.

Mr. Braine. that a storage very much less than the 132,484 acre-feet that he ha mentioned would give Nottingham a considerable measure o protection.

In Mr. Hillman's Paper no mention was made of one of the salien points in flood questions, namely, the great variation in the dis charging capacity of adjacent lengths of a river, which governe the design of most remedial works. That point was exemplified b a stream for which the President had recently been responsible fo providing some measure of flood-relief, and with which Mr. Brain had been concerned. The discharging capacity of that strea running "bank-full" had varied by more than $\pm$ 50 per cent. i several places over comparatively short lengths. At the point a which relief had been provided the stream-capacity was 600 cusecs but at a short distance downstream it fell to 300 cusecs, while at abou a mile further down it rose to nearly 1,000 cusecs. To reduce floodin in the central section arrangements had been made to abstrac about 300 cusecs from the stream by means of a siphon spillwa at the beginning of that section. Such a spillway provided reasonabl accurate automatic control, and, moreover, entailed no interferenc whatever with the normal regime of the river until it was runnin "bank-full." Mr. Hillman had stated that a by-pass had no effec upon flood-levels downstream of the point at which it rejoine the river. That was not quite correct, for, in an extreme case, i the by-pass were short and the river meandered more than usua the portion of the flood taken by the by-pass would pass back int the river long before the remainder of the flood that had bee travelling along the river arrived at the downstream end of th by-pass. Clearly the resulting hydrograph at that point woul show two flattened peaks, instead of one sharp one. He admitte that in practice the operation of a by-pass was seldom so favourabl as that, but it had to be remembered that the true function of by-pass was to relieve local flooding, as had been done in the cas he had mentioned, and not to lower flood levels downstream. H believed that a tin-mining company in Kuala Lumpur, F.M.S., ha offered to dredge a by-pass through the swamps above the town, bu the offer had not been accepted because it had been feared that Kual Lumpur would suffer worse than before, as the water would not b able to get away quickly enough; that was another illustration o the effect upon floods of the discharging capacity of different lengt of the same river.

Mr. Howorth. Mr. Ben Howorth observed that Mr. Hillman had given it his opinion that the ratio of high-flood flow to bank-full dischar might be taken as 3 to 1. In the case of the river Lee that rat was very nearly 2 to 1. It was essential that quantitative data

lood-flows should be obtained, but that took a long time, and it was Mr. Howorth. ıever certain that any figures so obtained gave the real maximum. ndeed, from experience of floods over a fairly long period, it ıight be said that the only factor known for certain was that ome day there would be a yet bigger flood than had previously ccurred.

The provision of reservoirs to impound sufficient flood-water to ıave any real effect on the flood-levels was almost impossible in England except at an uneconomical cost; that was clearly shown y the calculations in the Paper. It could not be too strongly mphasized that the combination of flood-storage and water-supply eservoirs was physically impossible. The case of the river Lee llustrated that point. For a length of nearly 8 miles along that iver there were water-supply reservoirs occupying nearly the whole vidth of the valley, and practically the whole of the water in the eservoirs was abstracted from the river. If the reservoirs were mpty, or even partially so, at the beginning of a flood there would e little need for providing extensive flood-relief works in the valley elow the site of the top reservoir. That condition, however, ever occurred; during most flood periods the reservoirs were ıll, and as they occupied the sites of the old flood-marshes they ndoubtedly added to the difficulties of getting rid of floods.

Mr. CLARK, in reply, stated that it was usual to allow $\frac{1}{4}$ inch of Mr. Clark. ainfall per 24 hours (or approximately 25 tons per acre), for effiiently draining an area by pumping. In the case of St. Germans, e had provided for $\frac{1}{5}$ inch, or 20 tons per acre, per 24 hours, and ıdging by the flood over the area during the recent winter, it was mple under present conditions. In any case provision had been ıade in the south engine-house for the installation of a further umping unit, if it was required.

He agreed with Mr. Binnie that efficient drainage was responsible r the high degree of fertility of the land, and was necessary for its rotection. The value of the land naturally varied, but it might e taken as from £30 to £100 per acre. If the drainage-system had ot existed, or was not maintained, the land would, in course of me, become inundated and practically valueless. The shrinkage f the area was not uniform, being very little in the areas of silt ıd clay. On the other hand, the de-watering of the peat-areas as one of the causes of the difficulty. Mr. Clark agreed with Mr. ıner that the cost of dredging the Ouse estuary would be enormous, ıd without training walls the dredged channel would soon silt up gain. The cost of dredging from St. Germans, with suitable traing walls, might be in the neighbourhood of £2,000,000. The cost f electrical supply was more or less determined by the load-factor,

Mr. Clark. which, over an average year, would probably not exceed 1,00 pump-hours.

Mr. Clark had considered automatic control in smaller plants i order to eliminate wages, but it was found that men had to b employed to clear the suction side of the pumps of weeds. In th case of St. Germans, slow-running variable-speed motors would b costly. The reinforced-concrete apron on the tidal side appeare thin on account of its length, but it should be borne in mind tha that apron under the lowest tidal conditions was submerged to depth of 9 feet, and that had a cushioning effect when dischargin by pumping, and protected the apron against scour.

With regard to the running of the pumps during the wet seaso of 1935–36, Mr. Silcock would be interested to learn that from 1 November to the date of the meeting all the water had bee pumped at St. Germans and none had been discharged by gravita tion, as had hitherto been the method. Allowing the rainfalls o September and October, which together amounted to 5·43 inches to saturate the land after the drought-period, the rainfall over th drained area from 1 November to 29 February was about 175,000,00 tons. During that period the pumps had worked about 1,600 pump hours, and had discharged approximately 70,000,000 tons. Th water-level in the area had been controlled and in several case minor internal districts had been able to gravitate into the Middl Level. The water-level at March, which was 17 miles from St Germans, had been kept at a lower level than the low-tide level a St. Germans. The Main Drain had been of sufficient capacity, bu the run-off, or the supply to the pumps, had not been sufficient t keep the pumps at their maximum output. The surface gradien in the Main Drain was about 4 inches to the mile. Before St Germans was decided on as the site for the new pumping-station two other sites were considered, one of which was at Upwell. Th disadvantages of the Upwell site were that it would have cost 4 per cent. more; the wire-drawing effect through the aqueduct woul have necessitated large culverts under Well creek; the aqueduc would be submerged; a minor pumping-station would have ha to be installed about 2 miles from St. Germans to pump from the land, from which the water already gravitated. Further, staff would have had to be kept both at the Upwell pumping station and at St. Germans, and the system would have perpetuate the troublesome double-reverse bend by gravitating through th sluice put in in 1880. Again, the raising of the banks on the side o the Main Drain would have been objected to by the adjacent owner who already complained that during flood times those banks leake so badly as to increase their pumping-charges.

With regard to Sam's Cut, the conditions at the Middle Level were Mr. Clark. ot comparable. In the first place, Sam's Cut was a small waterway hich discharged into a non-tidal river, whereas the Middle Level Iain Drain was, in reality, a river, having a bottom width of 60 feet nd discharging directly into the tidal river. Navigation above Jpwell had to be provided for in the Middle Level, and the area as served by about sixty pumps. It might be of interest to note hat of the Middle Level drained area, 60 per cent. was pumped, nd the remainder was composed principally of land rising to over 00 O.D. which gave a quick run-off. The figure given for the hrinkage of the Fenland, namely ½ inch per annum, was an average gure taken from several different points in the Middle Level area, nd it appeared that Mr. Borer more or less agreed with that gure. In dry seasons it might be more, but in wet seasons it ight be somewhat less.

With reference to Denton fen, which was apparently Whittlesey ere, that was a special case of a lake or mere being de-watered, nd could not be placed on the same basis as ordinary fenland. As e fen sank the clay would be nearer to the surface, and the shrinkage ould then be less than before. In the future, the Middle Level ould be faced with the shrinkage-problem in some areas, and it ight be necessary for the minor internal districts to take a share in e solution of the problem when it arrived. It was agreed that if e Middle Level had continued to discharge at Tong's Drain, the osition in the area would have been hopeless from a drainage point view.

When the reinforced-concrete piles were driven, the bottom did se, as suggested by Mr. G. J. Griffiths, but that action was most oticeable when the raking piles were being driven. Credit should given to Mr. Hill, the Resident Engineer, and his staff for the high rcentage of undamaged pile-heads. Great care had been taken in sembling the steel-work for the reinforced-concrete piles, and doubtedly they had had fairly hard driving.

Mr. Clark was obliged to Mr. W. M. Griffith for confirming the rise low-water tide readings between 1888 and 1912, and also for certaining the cause. It might be of interest to note that the ishing of silt up the river had not been eliminated, as the Middle vel sluice, built in 1880 and discontinued in September, 1934, had ice accumulated 13 feet 6 inches of silt on the sill. With reference the scouring action of Denver sluice, Mr. Clark thought that its ect would not be felt very far down the river. At the same time, agreed that by lengthening the periods of discharge of upland ter, the tendency was to keep the silt in suspension as it came o the estuary in the lower reaches of the river. It had often

Mr. Clark. been asked whether it would be possible at St. Germans to pump ar to gravitate at the same time. That was not possible, as the wate level on the suction side during pumping was below the low-wat tide-level. It would be understood that the pumps at St. Germa were used to take the peak off the flood, and that as much as possib was discharged by gravitation. So far, from reports from th internal districts, the results during the past winter had bee satisfactory.

Mr. Hillman. Mr. Hillman, in reply, referred to the point raised by Mr. Binn as to the effect of a by-pass channel; Mr. Hillman desired to mal it quite clear that in his contention that such a channel could no alter the discharge he purposely neglected the fact that the chann might have the effect of reducing the storage-capacity. A by-pa channel would certainly lower flood-levels locally, but any alteratic of the discharge was, it was submitted, caused directly by variatio in storage-capacity, and only indirectly by the presence of the by pass channel. In that connection Mr. C. D. C. Braine cited th special case of a cut-off whereby theoretically the hydrograph woul be split into two peaks, separated in the time-scale by the differen of time taken by the peaks in travelling unequal distances. I practice, however, that time difference was likely to be very sma in comparison with the duration of a flood, and it was doubtf whether the flattening effect on the hydrograph, although certain admitted, would be measurable.

With regard to storage-reservoirs augmenting floods, Mr. Hillma had in mind an occurrence by no means uncommon in Ceylon (an no doubt, in other parts of the world), where a series of irrigatic reservoirs or "tanks" were constructed in succession down a rive valley. Hundreds of such tanks existed in Ceylon, many of whic were abandoned or uncontrolled. In most cases they had natur spills at the ends of the bunds. Frequently one of the upper-tan bunds was breached, due to a local storm; the water flowed int the next tank immediately below, breaching that also. The com bined flow then proceeded to breach all the following tanks in su cession, causing a disaster of no little magnitude. It was true th the direct cause of the trouble was insufficient spill-accommodatio but nevertheless that was a case where uncontrolled reservoi greatly augmented floods.

While in no way disputing the fact that a reservoir, even if fu might still afford considerable storage-capacity above spill-leve Mr. Hillman drew attention to another point which might have bee overlooked, namely that the run-off-coefficient of a water surfa was 100 per cent., whereas that of land was likely to be very muc less than that figure. He considered that it was a debatable poi

s to whether the advantage of the storage-capacity was not more han outbalanced in certain cases by the increased run-off-coefficient. 'urther, because the function of a reservoir was to delay and to educe the level of a flood-peak, it by no means followed that that ras an advantage. If the reservoir was on a tributary stream to a aain river, it might well happen that the delayed peak in the tribuary might coincide with the peak in the main river, causing a higher ood in the latter than would otherwise have been the case. The ontrary was naturally also true; that was to say, a delay on one tream might separate peaks, with consequent advantage. Mr. Hillman.

Mr. Binnie referred to the size of a reservoir, and stated that a eservoir area up to 5 per cent. of the catchment-area would have a ery considerable effect in reducing floods. The catchment-area of he Trent above Nottingham, for instance, was 2,800 square miles, nd 5 per cent. of that area was 140 square miles, or twice as large s the hypothetical reservoir computed by Mr. Hillman to be necesary to relieve Nottingham from floods. Mr. Hillman's contention as that the cost of constructing such a reservoir, with sluices capable f discharging at least 13,000 cusecs, would be out of all proportion the cost of flood-protection at Nottingham by other means. In ndeavouring to reply to Mr. Griffith's query as to cost, Mr. Hillman ad been unable to find a suitable site above Nottingham for such a servoir without entailing the drowning of several villages, as well s roads and railways; it would be quite impossible to estimate the ost.

Mr. Hillman did not wish to imply that reservoirs should not be sed for flood-detention. On the contrary, where the topography the country was suitable, they might be, and often were, so nployed most effectively; the Sacramento River Flood-Control lan was an example where reservoirs, by-passes, and embankments ere all used.

With regard to Mr. Saner's comments, thanks to the courtesy of e Trent Navigation Company the River Trent Catchment Board as very fortunate in having access to almost invaluable river-gauge cords from a number of gauging-stations, dating back to 1885. he Board had recently added a number of subsidiary stations, cluding automatic recorders both for ascertaining the variation in me of propagation of flood-waves, and also for the study of tidal ienomena in the lower reaches of the Trent, particularly with refer-ce to storm-surges in the North Sea.

On the question of the relationship between "high-flood" and bank-full" discharge, Messrs. G. J. Griffiths and Ben Howorth entioned that the ratios in the Thames and Lee might both be ken as 2 to 1. Mr. Griffiths, however, gave a peak-flow figure in

Mr. Hillman. 1929 of 19,404 cusecs, whereas the bank-full flow mentioned wa 8,325 cusecs, giving a proportion of 2·33 to 1. By "high flood" Mr. Hillman had intended to refer to the highest flood which migh reasonably be anticipated, and to deal with which flood-protectio work should be designed. He therefore considered that a ratio o 2 to 1 was too low, and that as a rough approximation 3 to 1 was safer estimate.

Mr. C. D. C. Braine had suggested that, although a reservoir o the size computed to be necessary to deal with major floods a Nottingham might be impracticable, works to eliminate minor flood might be considered. Mr. Hillman's view was that minor flood protection schemes, which would be liable to failure sooner or later were a grave danger, and were to be strongly deprecated. Th danger was that after such a scheme had operated successfully fo a number of years, building-development would take place, wit the result that, when failure occurred the disaster would thereby b seriously magnified, with a possibility of loss of life.

Regarding the variation of the discharging-capacity of adjacen lengths of a river, except in tidal reaches Mr. Hillman had not foun that the Trent varied to anything approaching the ±50 per cent mentioned by Mr. Braine. It was true that the cross-sectional area varied greatly, but the river sloped, and consequently velocitie automatically increased in the small sections and decreased in th larger sections, so that compensation was thus maintained.

*** The Correspondence on the foregoing Papers will be publishe later.—Sec. Inst. C.E.

ORDINARY MEETING.

3 March, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The Council reported that they had recently transferred to the class of

Members.

Philip Grosvenor Corin, B.A. (*Cantab.*).
Arthur Dyson.
Thomas Edwin Nelson Fargher, Ph.D., M. Eng. (*Liverpool*).
Thomas Andrew Steel Fortune.
William Bertram Hall.
Charles Herbert.
George McIldowie.
Gilbert Gould Marsland, B.Sc. Tech. (*Manchester*).
Walter Lancelot Moore.
Thomas Whitley Moran, B.A., B.A.I. (*Dubl.*).
George Ernest Samuels, B.A.I. (*Dubl.*).
Archibald Muir White.

And had admitted as

Students.

Harold Wilmot Archer.
John Woodrow Arnott.
Kenneth Alan Ballinger.
Thomas Mitchell Bell.
Christopher Booth, B.Sc. (Eng.). (*Lond.*).
Thomas Archibald Campbell Brownlie, B.Sc. (*Edin.*).
Henry Thomas Coggon.
Norman George Cooper.
Peter Lovell Cubitt, B.Sc. (Eng.) (*Lond.*).
Oliver Dawson, B.Sc. (Eng.) (*Lond.*).
Rupert Arthur George Eveleigh.
Walter Harriman Fletcher.
Alfred John Louis Gamper, B.Sc. (Eng.) (*Lond.*).
George Albert Gepfert.
Deryck Gibson.
Cyril Rowland Harman.
John Keith Hartley.
Andrew Hunter Hinrichs.
Douglas Alexander Hudson.
Alan Edward Jensen.
John Denys Marsh Lyons.
James Crichton Massie.
Daniel John Hyslop Morrison, B.Sc. (*St. Andrews*).
Peter Grey Mott, B.A. (*Oxon.*).
John Joseph Moynihan, B.E. (*National*).
Graham Francis James Murray, B.Sc. (*Lond.*).
George William Newton, B.Sc. (Eng.) (*Lond.*).
Osmond Ormiston, B.Sc. Tech. (*Manchester*).
Herbert George Perry.
William Glanvill Phillips, B.A. (*Cantab.*).
James Walter Pilling.
Norman Allan Pritchard.
Frank Cyril Ramsay.
Derek Neville Reed.
Kenneth Claude Revis.
Alexander Frederick Reynard, B.A. (*Cantab.*).
Andrew Cairns Ross, B.Sc. (*St. Andrews*).
Narayan Ganesh Shahane, B.E. (*Bombay*).
Douglas Urwin.
Herbert Leicester Keith Williams.
Leighton Melson Wingate, B.Sc. (Eng.) (*Lond.*).

The Scrutineers reported that the following had been duly elected as

Members.

George Davy Balsille.
Henry Nimmo.

Associate Members.

Roy Symington Alford, Stud. Inst. C.E.
John Gordon Barrett.
Reuben Winton Bell, Stud. Inst. C.E.
Charles Edgar Bennett.
John Torrington Blatchford, B.E. (*Western Australia*).
Geoffrey Boon, Stud. Inst. C.E.
John Hyde Bradley, B.A. (*Cantab.*), Stud. Inst. C.E.
Donald Anderton Brown, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
John Brown, B.Sc. (*Glas.*).
Sydney Arthur Burgess.
Thomas William Callagy, B.E. (*National*).
Louis Caplan, B.Sc. (*Witwatersrand*).
Joseph Edward Clarke.
Douglas Cecil Coode.
James Dyke.
Walter Tremayne Field, B.Sc. (*Cape Town*).
John McNeal Fisher, B.Sc. (*Manchester*), Stud. Inst. C.E.
Herbert Clifford Garlick, B.E., B.Sc. (*New Zealand*).
Charles Paston Browne Goldson, B.Sc. (*Durham*), Stud. Inst. C.E.
Charles Drummond Graham.
Albert Claypole Hall, M.Sc. (*Manchester*), Stud. Inst. C.E.
Clifford Harris, B.Sc. (*Cape Town*).
William Douglas Haworth, Stud. Inst. C.E.
Eric Ernest Hendriksen, M.Sc., B.E. (*New Zealand*).
Albert Edward Howard.
Herbert Maxwell Howells, B.Sc. (*Cape Town*).
Eustace William Aubrey Jackson, B.A. (*Cantab.*), Stud. Inst. C.E.
Eric Livingstone Janisch, B.Sc. (*Witwatersrand*).
Hugh Gounter Heneage Legge, B.Sc. (*Witwatersrand*).
Robert Lang Lindsay.
John Malone, B.Sc. (*Glas.*).
Neville Oliver Marriott, B.Sc. (*Cape Town*), Stud. Inst. C.E.
Henry Worgan Marshal, B.A. (*Cantab.*).
William Kelsey Masters, B.A. (*Cantab.*).
Arthur Harwood Maynard, Stud. Inst. C.E.
Thomas Henry Fancourt Nevins.
Lewis Paul, B.Sc. (*Edin.*).
Arthur Leslie Percy, B.Sc. (*Birmingham*), Stud. Inst. C.E.
Lyndsay Norman Prismall.
James Eldon Read, B.Sc. (*Witwatersrand*).
Hugh Murray Reid.
Alasdair Ian George Sutherland Robertson, M.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Arthur Willie Rolfe, B.Sc. (*Cape Town*).
Basil William Rowe.
Alexis Nicolaas Sandenbergh, B.Sc. (*Witwatersrand*).
James Reginald Walter Saunders, B.Sc. (*Glas.*).
John Hugill Snell, B.Sc. (*Witwatersrand*).
Wilfrid Hardy Spencer, Stud. Inst. C.E.
Herbert John Steed, B.A. (*Cantab.*).
Norman David Evans Stephens, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Philip John Stuckey, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Douglas von Sturmer.
Keith Edmonds Trask, Stud. Inst. C.E.
Arthur Cecil Tregoning, M.C.E. (*Melb.*).
John Graham Welsh, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Authors.

"Road Engineering Problems: Judging the Slippery Road."

By Reginald George Cyril Batson, M. Inst. C.E., George Bird, B.Sc., and Reginald Edward Stradling, C.B., M.C., Ph.D., D.Sc., M. Inst. C.E.

TABLE OF CONTENTS.

Introduction.

The research dealt with in this Paper is not yet complete, but the results are laid before The Institution at a time when criticism from the practical engineer is essential if the work is to progress along the lines of maximum utility and speed.

The problem considered in this Paper is very urgent, and is of a wider interest than the merely technical side of road construction, since it is of vital importance to all road-users. It is not suggested that defective road-surfaces are more than a relatively minor factor in the causes of road-accidents; since, however, road-surfaces are the special care and duty of the engineer, it is obviously of great importance that he should have available an instrument for measuring slipperiness. He may then be able to sort out this factor, which is his responsibility, from those more personal ones of a physiological or psychological character for which, as an engineer, he can scarcely be held responsible.

During the last 5 years a considerable amount of work has been done in devising machines for measuring slipperiness and in carrying out investigations on the roads themselves, and it is suggested that a practical measuring device is now available and should be used by road-engineers; the practical experience thus obtained will help to bring about a greater understanding of the problem of slippery roads, and may possibly enable a further simplification to be made of the apparatus itself. A measuring instrument, however, can at the best only give a numerical value; it must of necessity be the engineer's responsibility to interpret this value and apply it to road-practice.

The Measuring Instrument.

About 6 or 7 years ago the Ministry of Transport requested the National Physical Laboratory to attempt to design a machine capable of providing information on the frictional properties of actual road-surfaces. This was done and a description was published in a paper by Messrs. J. Bradley and R. F. Allen.[1] The machine consisted of a motor-cycle and sidecar, the load on the sidecar-wheel and the tangential force at the road-surface being measured when the vehicle was driven at various speeds: (*a*) with the sidecar-wheel "skidding" sideways, and (*b*) with the sidecar-wheel revolving in the direction of motion, but braked in order to give tractive resistance. The sideways tangential force divided by the load was called the "sideways-force coefficient," and the retarding force divided by the load was called the "braking-force coefficient." Both these coefficients were really coefficients of friction determined under defined conditions and having approximately the same value.

The results recorded by the National Physical Laboratory were sufficient to show that the method employed was satisfactory for the purpose in view. The machine was then taken over by the Ministry of Transport, by whom it was modified to increase the engine-power and to enable the measurements to be recorded more conveniently. The method has been in use now for about 5 years. Detailed descriptions [2] of both the method and the results will shortly be published in a series of Road Research Technical Papers and Bulletins, so a mere outline is given here.[3]

A diagrammatic plan view of the machine, with the sidecar-wheel in its test-position to give sideways skidding, is shown in *Fig. 1*. The wheel is fixed at an angle to the direction of motion and the sideways thrust on the wheel is transmitted to a dynamometer G by a strut-bar K. The sideways-force dynamometer G is carried on a plate H attached to the pivot of the sidecar-wheel A, the plate being supported by a second plate bracketed to the main

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[1] "Factors affecting the Behaviour of Rubber-Tired Wheels on Road Surfaces," Proc. Inst. Automobile Engineers. Vol. XXV, p. 63, Nov. 1930.

[2] Road Research Technical Paper No. 1. "Studies in Road Friction. (1) Road-Surface Resistance to Skidding."

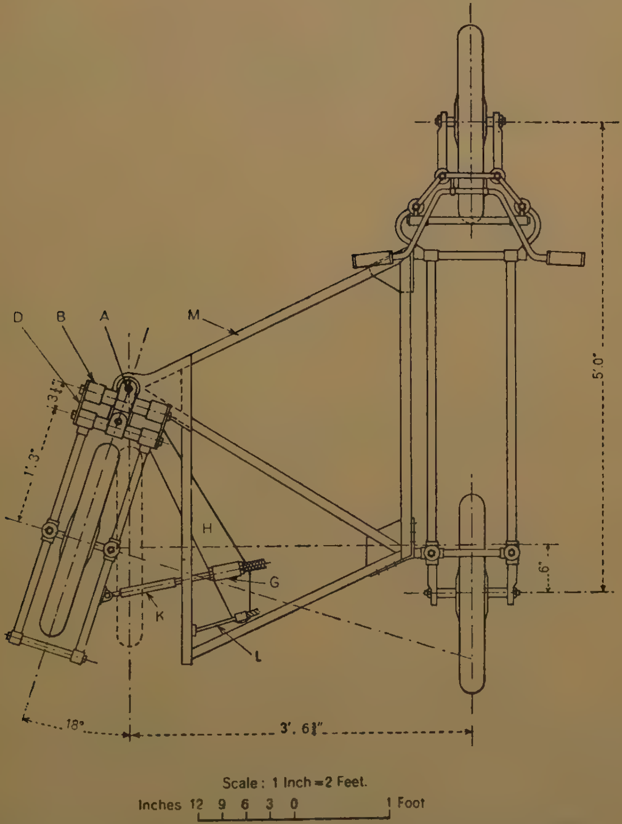
Road Research Bulletin No. 1. "Measurement of the Non-Skid Properties of Road-Surfaces."

These will be issued jointly by the Department of Scientific and Industrial Research and the Ministry of Transport.

[3] The apparatus itself was exhibited at the Institution on the evening when the Paper was discussed.

chassis M. The reaction on the dynamometer is taken by a Bowden cable L, which allows the inclination of the wheel to be adjusted. A second dynamometer (not shown in *Fig. 1*) gives the load on the wheel. Each dynamometer consists of a plunger fitting in a cylinder, and the load is transmitted by oil-pressure in the cylinder through a pipe-line to another cylinder, with a spring-loaded plunger, in an

Fig. 1.

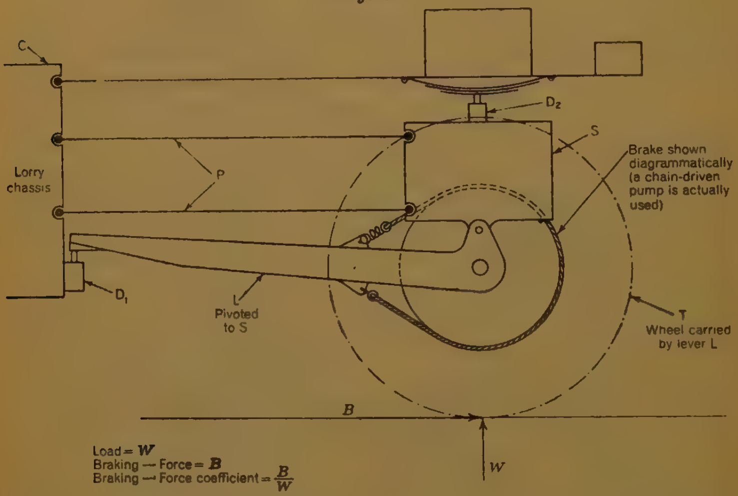


instrument-box attached to the sidecar. The movement of this second plunger is then proportional to the force or load on the first plunger. The movements of both the sideways-force- and load-plungers are combined by a special link mechanism to give a trace on a chart. The ordinate recorded is proportional to the ratio $\frac{\text{sideways force}}{\text{load}}$, and is therefore proportional to the sideways-force coefficient.

From the point of view of research, the restrictions imposed by this apparatus are those of one size of tire and one load, and it has been thought desirable to explore the effect of variations in these factors as far as circumstances allowed; for this purpose a new apparatus has been constructed. Evidence available from tests carried out in Germany, France and the U.S.A. appears to indicate that the effects, if any, are small.

The apparatus has been designed to be towed by a lorry on the road or on a large road-testing machine, and the principle of the apparatus is shown diagrammatically in *Fig. 2.* It consists of a test-wheel T of the quickly-detachable type, mounted at the end of a spindle carried on a lever L. The braking-force tends to tilt this

Fig. 2.



lever and the force required to keep it in position is measured by means of a dynamometer D_1. In *Fig. 2* a rope-brake is shown for simplicity but, in the actual apparatus, braking is applied by means of an oil-pump driven from the test-wheel through a roller-chain. A valve on the delivery side of the pump is used to regulate the pressure. The support S for the lever is carried by parallel links P from the lorry C which is used to tow the apparatus. The load W carried on the wheel is partly mounted on a spring platform and is measured with the assistance of a second dynamometer D_2. The slip of the braked wheel is measured by comparing its revolutions with those of the front wheel of the lorry, both wheels being fitted with electric contacts.

The apparatus therefore measures braking-force coefficients.

Previous work with the sidecar apparatus gave indications that braking-force and sideways-force coefficients were approximately the same for the same surface, but this point is being verified by simultaneous tests with both types of apparatus when fitted with the same type and size of tire. Since the machines described are used to compare road-surfaces, the tread of the tire employed must be of a standard form ; that is, it must not vary throughout a test or from test to test. This involves the use of smooth treads to the tires.

Some recent work carried out by Mr. F. G. W. King has some bearing on this point, although his conditions of test are not strictly comparable. He reports [1] tests made by measuring the retarding force and draws the following conclusions :

(1) Smooth tires are, on the whole, equal to new tires on dry surfaces.
(2) With new tires there is no great difference in the stopping-distances on dry and wet roads.
(3) With smooth tires there is a very great difference between dry and wet conditions on certain surfaces.
(4) On smooth icy surfaces, new and smooth tires are equally bad.

He also states that there is a smaller difference between the best and worst tires from sideways-slipping tests than in straight-slide braking-tests.

These conclusions indicate that smooth tires give a greater differentiation between the skidding properties of surfaces than new tires. Further, in spite of the fact that smooth tires are not permitted, a visual inspection of tires used to-day shows that a large number of smooth-tread tires are still employed.

The Problem of Slippery Surfaces.

The curves obtained by the Road Research Laboratory, and given in *Fig. 3*, are characteristic for widely-differing surfaces. Curve (1) is typical of results obtained on all dry surfaces and upon some kinds of wet surfaces. It represents a high resistance to skidding. Curve (3) at the other end of the scale shows low sideways-force coefficients, even at low speeds. A surface giving this type of curve would undoubtedly be characterised as dangerously slippery. Between these two extremes there are other types of surfaces, from one of which curve (2) is given as an example.

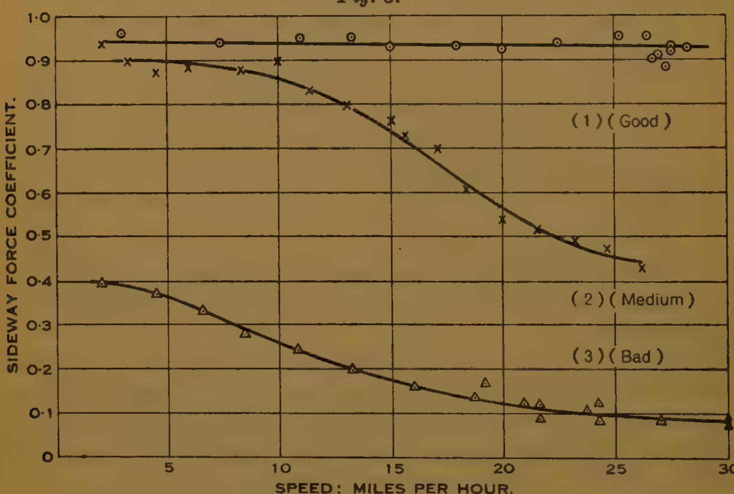
The ideal condition is for all road-surfaces to give curves similar

[1] Paper read at the British Association Meeting at Norwich, 13th September, 1935. Abridged version in *Engineering*, vol. 140 (1935), pp. 467–470.

to (1), and new surfacings and surface-dressings can be provided which answer this requirement, but road-engineers require to know how far they can let an otherwise satisfactory surface deteriorate in this respect before adopting remedial measures. The safety of such surfaces, from the point of view of skidding, depends upon various considerations, such as the layout of the road and the traffic conditions. The fact that all dry surfaces give sideways-force coefficients which are independent of speed, while wet surfaces show a lowering of the coefficient with an increase in speed, suggests that some influence is present in wet surfaces which is akin to lubrication.

In a recent paper, Dr. R. N. G. Saal [1] elaborated this idea and

Fig. 3.



showed that a theory—based on Osborne Reynolds' theory of lubrication—fitted the experimental observations obtained by the motor-cycle and sidecar described above, and also agreed with the results from a small-scale laboratory apparatus which he constructed for the purpose.

The theory presupposes that a lubricating film exists on the road and that the frictional resistance depends upon

(1) The type and viscosity of the lubricant.
(2) The thickness of the lubricating film.
(3) The roughness (or " knobbliness ") of the surface.
(4) The absorptive capacity of the road-material for the lubricant.

[1] " Investigations into the Slipperiness of Roads," Journal Soc. Chem. Ind., 3 Jan. 1936, p. 3.

When a loaded wheel rolls over a road-surface on which there is a lubricating film, the entire sideways frictional resistance is taken in the film so long as the film is unbroken. The resistance under these conditions is very low and is typified by that obtained on ice, where there is always a film of water between the tire and the ice-surface, and where coefficients (independent of speed) of the order of 0·10 have been recorded. Where the film is broken by projections on the road-surface, only part of the contact area has a lubricating film interposed, while the remainder gives "solid" friction. The frictional force then depends on the relative proportions of these two parts.

The reduced frictional force at high speeds may be caused either by

(1) Less time for the film to break down.
(2) An increase in the viscosity of the lubricant.
(3) A gradual building-up of the lubricant in front of the wheel until the tire rides over the film. With high speed this building-up may increase, thus causing a thicker film and a smaller proportion of "solid" friction.

Dr. Saal has shown that the frictional force decreases with increasing viscosity of the lubricant. It should be borne in mind, however, that viscosity may increase with pressure, and hence the viscosity as measured by a standard viscometer at atmospheric pressure may not be necessarily the same as the viscosity of the liquid under the tire. On a dry surface the whole of the friction is "solid" friction and is independent of the speed.

The study of the problem of slippery roads from the point of view of the road-surface therefore involves two factors :—

(1) The lubricating film.
(2) The roughness of the surface or other attributes of the surface preventing film-formation.

(1) *The Lubricating Film.*

Dr. Saal, in the paper to which reference has been made, gave values of the sideways-force coefficient for various lubricants obtained with his small-scale apparatus. They were obtained on sheet asphalt at an equivalent road-speed of 25 miles per hour, and are given in Table I.

Dr. Saal stated that the chalk could be taken as consisting of large-sized particles and the clay as consisting of fine particles, and that the value of the coefficient decreased with increasing viscosity. The results clearly demonstrated the importance of the composition of the lubricating film on skidding, and indicated the

desirability of continued investigations into this aspect of the subject.

From similar work at the Road Research Laboratory one result may be of interest. An experimental section of road had been laid on a public highway to test a proposed new type of road-surface. After a period the surface was reported as a very slippery one and the Road Research Laboratory was asked to carry out measurements with the motor-cycle combination. This was done, and at the same time the opportunity was taken to remove for analysis some of the liquid forming the surface film. The measurement of the sideways-force coefficient on the road itself gave a very low result, namely, about 0·15 at 30 miles per hour, and 0·30 at 5 miles per hour. The liquid was tested in the Laboratory under conditions of film lubrication, and gave a value of the coefficient of friction of 0·12 at 3 miles per hour; for this test the liquid was used as a lubricant between a rubber wheel and a glass plate. The analysis of the dirty liquid showed that it contained about 5 per cent. of detrital matter from the road, about 0·1 per cent. being suspended in the solution in a colloidal state. The analysis of the 5 per cent. of detritus showed it consisted of approximately 75 per cent. fine mineral matter, the remainder being organic.

TABLE I.

Type of Lubricant.				Sideways-force coefficient.
Water: per cent.	Chalk: per cent.	Clay: per cent.	Lubricating Oil: per cent.	
100	—	—	—	0·55
75	25	—	—	0·54
75	12½	12½	—	0·20
75	8½	8½	8	0·17
50	25	25	—	0·10

(2) *The Roughness and Other Attributes of the Surface.*

There are many different views as to the type of surface-finish which gives the best resistance to skidding. A coarse open surface appears, from a visual examination, to be the best, but, to judge from the opinion expressed by some engineers, this may not be necessarily the case.

The British Standard Specification for Hot Asphalt (B.S.S. 594) specifies "with a view to providing a roughened surface, the asphalt, after initial compression and while still warm and in a plastic condition, shall be covered with a layer of approved clean hard chippings, all of which shall pass a $\frac{3}{4}$-inch-mesh sieve and be retained on a $\frac{1}{2}$-inch-mesh sieve." The chippings may be coated with asphaltic cement prior to application, or they may be left uncoated. It is known that some engineers consider the above procedure to be unnecessary on single-coat stone-filled asphalt, but it is also known that experimental sections on the Kingston By-Pass have shown that the addition of precoated chippings during construction will give a non-skid surface for at least 5 years.

There are many advocates for a "sandpaper" finish on asphalt, and this is possibly based on the experimental work of Professor Moyer [1] in the U.S.A. Surface-dressings of roads which have tar or residual bitumen as the binder often incorporate $\frac{3}{4}$-inch chippings as the cover. Some engineers prefer to use smaller chippings, while some trials have been made with graded chippings, with or without sand.

It will be realised that practical experience is not unanimous on this point of surface-texture, though it would be safe to state that if a rough open-textured surface is present, and is not so thickly covered with a "lubricant" that it is obscured, then the surface is definitely "non-skid," and further that it would require much more to obscure such a surface as compared with, for example, a so-called "sandpaper" finish.

RESULTS.

Whatever the final truth about surface-texture and its interaction with lubricants and tires, the point to be emphasized in this Paper is the existence of an apparatus which, if adopted by the road-engineer, will enable him to obtain an actual measurement of the frictional resistance of a particular piece of road under a given set of conditions.

Some generalized results of measurements have been given in *Fig. 3*, and the following are a few typical examples taken from Road Research Technical Paper No. 1, "Road Surface Resistance to Skidding," which will shortly be published.

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[1] "Skidding Characteristics of Automobile Tires on Roadway Surfaces and their Relation to Highway Safety," R. A. Moyer, Iowa State College of Agriculture and Mechanic Arts, Bulletin 120, Aug. 1934.

TABLE II.

Surface.	Sideways-force coefficient under wet conditions at 5 miles per hour.	20 miles per hour.	30 miles per hour.
New cement-concrete	0·90	0·80	0·75
Old cement-concrete	0·90	0·65	0·50
New tar-concrete with precoated chippings	0·90	0·90	0·80
Same surface after 4 years :—			
Winter	0·90	0·80	0·70
Summer	0·85	0·60	0·40
Freshly-laid surface-dressing on old tar-macadam	0·90	0·90	0·80
Worn surface-dressing in winter	0·80	0·45	0·30
New single-coat hot asphalt with precoated chippings, in winter	0·95	0·90	0·85
Same surface after 4 years :—			
Winter	0·95	0·85	0·75
Summer	0·85	0·70	0·55
New compressed rock-asphalt with precoated chippings, in winter	0·95	0·90	0·90
Same surface after 4 years :—			
Winter	0·95	0·90	0·80
Summer	0·85	0·75	0·65
Old compressed rock-asphalt with no surface-finish	0·30	0·15	0·10

Note.—Under dry conditions all normal clean surfaces give sideways-force coefficients of 0·80 or more at 30 miles per hour.

It will be seen that the sideways-force coefficient can vary, under wet conditions, from 0·1 to 0·9 at a speed of 30 miles per hour, and from 0·3 to 0·95 at 5 miles per hour. The investigators concerned have come to regard a value of 0·5 and above at 30 miles per hour as typical of a good non-skid road, whilst a value of less than 0·2 at 30 miles per hour is regarded as definitely unsafe. Such statements, however, cannot be accepted as universally true, especially at the lower end of the scale, for, as shown by the work and also from common experience, the tendency to "skid" depends upon speed. Thus, in some instances it has been found that surfaces of streets of big towns, which are subjected to the heaviest form of traffic, show a low value for the sideways-force coefficient at 30 miles per hour when wet; since, however, the traffic they carry is chiefly slow-moving, they are reasonably free from accidents due to skidding.

The translation of the numerical value obtained from the machine into a judgement as to the safety of a particular road cannot be

done without taking cognizance of the other factors which enter into the problem, and this is the engineer's particular duty. These other factors are those relating to the type of traffic, the siting and planning of the road and the general conditions locally. There can, however, be no doubt as to the guidance which the engineer may obtain from an instrument which will give him a measurement of the surface condition, while if he had the machine always at hand he would have a ready means of checking complaints and of keeping records of the rate of deterioration of his surfaces.

If this type of apparatus can be adopted as an every-day tool of the road-engineer, a quantity of knowledge would soon accumulate which would help to clear the whole outlook on slippery road-surfaces, and would soon render the interpretation of the numerical results an extremely easy matter. Until this further practical experience has been obtained over a wide area, embracing the many variable conditions found throughout the country, the research work already carried out cannot be fully effective. The assistance of the staff of the Road Research Laboratory in the specification for purchase is offered to engineers who decide to use the machine, and it would be possible to arrange for some training in the handling of the machine and the interpretation of the results if engineers or their assistants would care to take advantage of this offer. The co-operation of the practical road-engineer is urgently required, and in return it is believed that a useful tool is offered which, with proper use, should do much towards giving warning of unsafe road-surface conditions.

Discussion.

Dr. Stradling.

Dr. Stradling, in exhibiting some lantern-slides illustrating th Paper, said that in submitting it the Authors had taken advantage of the invitation extended to them by The Institution to bring forwar for discussion investigations which were still unfinished. Th Authors were anxious to bring the work to the notice of The Institu tion because they felt that the next step must be taken by practic engineers, and they hoped to induce engineers who were concerne with road-problems to utilize the apparatus which was now availab for them. They therefore wished to make that apparatus as wide known as possible. It was practical, easily handled, and simple t understand, and it should be of very great service to the road engineer. There was, however, little more work that the Roa Research Laboratory could do on it until its use could be extende over a wider field; they would like to persuade engineers througho the country to adopt it.

Referring to *Fig. 3*, he mentioned that the road whose properti were represented by curve (3), which was labelled "Bad," ha previously been the subject of complaints, and had to be put righ Roads of that type were fairly rare, most roads giving results comi between curve (2) and curve (1).

With regard to Table II, it would be observed that the sideway force coefficients were found to be lower in summer, when the tes were made during showers, than in winter, when the roads had mo continuous washing by rain.

Referring to the discussion in the Paper of the relative merits the "sandpaper" and the rougher types of finish, he suggested th in that connection the practical experience of road-engineers wou be of great value. If, as the work described in the Paper appear to indicate, the liquid film on the surface of the road was the cau of slipperiness, then it would appear that with a given amount film the chances of getting solid friction were very much higher wi a rough surface of, say, $\frac{3}{4}$-inch chippings than if the film were sprea over a relatively smooth surface. It could not be assumed, howeve that that would necessarily be the case. Since the date on whi the Paper was originally to have been presented,[1] his colleagues the Ministry had shown him a road which had a surface of $\frac{3}{4}$-in chippings, and yet had a poorer sideways-force coefficient,

[1] 21 January, 1936.

easured by the machine described in the Paper, than other roads Dr. Stradling.
hich, judged by the eye, seemed very much smoother. On looking
ito the matter, the trouble appeared to be due to the fact that the
ctual chippings themselves were smooth and flat, so that the surface
ave the impression of consisting of a miniature series of cobblestones.
; seemed therefore impossible to lay down any definite general rules
or the attainment of a non-skid surface, but he thought that the
nance of non-interference by a lubricating film must be relatively
igher with a very rough surface, provided that the chippings were
f suitable shape.

He would like to emphasize that any county or city engineers who
dopted the machine could rest assured that every assistance would
e given to them by the Road Research Laboratory.

Mr. BIRD exhibited and explained two cinematograph films illus- Mr. Bird.
rating the testing-apparatus in use.

Mr. F. C. COOK remarked that those who had been concerned with Mr. Cook.
oad administration for a long period would well remember the time
hen the dust nuisance was the chief problem. As so often
appened, the solution of that problem had introduced another, and
was the necessity of measuring the slipperiness of various road-
urfaces, following on the application of impervious, smooth surface
oats, which led the Ministry of Transport to approach the National
hysical Laboratory about 8 years ago and ask them to design the
achine which was described in the Paper. He was told that in
930 Messrs. Bradley and Allen had expressed their willingness to
resent a Paper describing that machine to The Institution, but the
aper was not in fact presented, presumably because at that time it
as thought that the subject was not of sufficient general interest.
was a welcome indication of the change of outlook and of the
ppreciation of the fact that scientific principles should be brought to
e solution of road problems that the present discussion was taking
ace. The first machine was used with success over a period of some
ears, that success being largely due to the skill of Mr. Bird. The
sults which the machine gave were singularly in accord with practi-
l experience of road-conditions.

He would like to stress the Authors' suggestion that a machine of
e type in question ought to be regarded as a normal item of the
ant of, at any rate, the larger highway-authorities. The Paper
entioned several respects in which such a machine would be useful
them, but there was another to which reference might be made,
mely, that it would enable a road-engineer to rebut, if necessary,
th some degree of certitude the statements, often misleading, which
ere made concerning the alleged slipperiness of a particular road,
ten as the result of observation which was prejudiced or misleading.

Mr. Cook It would also enable the road-engineer to obtain a really accurat picture, based on scientific data, of the extent of the problem of roa slipperiness in the area for which he was responsible.

With regard to the extent of the problem, two years ago th Ministry of Transport conducted investigations into all cases wher road-conditions were alleged to have been the cause of fatal accident. In the year in question there were 6,942 fatal accidents, and of thos 149 were alleged to be due to skidding. All those 149 cases wer investigated by the divisional road-engineers of the Ministry, and was shown that in 82 of them the diagnosis might be regarded a correct, so that 1·3 per cent. of the total number of fatal accidents i that year could definitely be attributed to skidding caused by th road-surface. He mentioned those figures with some reserve firstly, because they might be thought to lead to some degree c complacency in the minds of road-engineers, which was not in fa the case; and, secondly, because the dividing line between a fat and a non-fatal accident was very fine indeed, and might be co sidered to depend either on the interposition of a merciful providen or the skill or good fortune of the individual concerned.

It was perhaps true to say that in no aspect of road-engineeri had a greater advance been made in recent years than in the pr vision of a non-skid surface. In the early days of water-bound roa coated with an impermeable smooth surface there were many co plaints of slippery conditions, and in 1929, after consulting ma highway-engineers, the Minister of Transport issued a circular which it was suggested that use should be made of larger-gra chippings than had previously been the case. On the whole, t results were excellent, and he thought it would be agreed that the had been a very marked improvement in the technique of surfa dressing, certainly within the last 5 or 6 years. An extended l had been obtained, and surface-dressing was no longer regard as an annual process; a life of 2 or 3 years or even more w now obtainable. Further, the area of road-surface dressed each year was becoming less and less, owing to the method wh was now being adopted of securing a non-skid surface by the appli tion of a thin surface-coat, possessing an inherent non-skid prope of its own, which would remain non-skid for a considerable num of years. The Ministry of Transport, with the co-operation of hi way authorities, had laid no fewer than forty sections of roads that character in different parts of the country, formed of thi different materials. There had been occasional failures, but on t whole the results were extremely promising. It had to be reme bered that, besides bad road-surfaces, there were other fact which tended to induce skidding. Those factors included

lignment, grading, and particularly the camber of the road, the Mr. Cook. esign of the vehicle, the type and condition of the tire, the character-stics of the driver, and the effect of the conduct of other road-users pon his actions.

Although great advances had been made in the production of easonably non-skid surfaces, the root cause of road-slipperiness had et to be determined. The Paper indicated that the presence of a ıbricating film was undoubtedly the principal agent in that respect, ut its composition and source had yet to be discovered. If it were ue to exudation of the binder, what were the characteristics which aused it, and how could they be eliminated? If external sources ere responsible, was the film due to the deposition of soot or of ust, to attrition of the road-surface, or to attrition of the tire? The ngineer could not determine such questions for himself; they were ssentially matters for laboratory investigation, and Dr. Stradling as now carrying out at the Road Research Laboratory investiga-ions which should be very helpful in those directions.

Further progress in the production of safe road-surfaces was ırgely in the hands of road-engineers and of manufacturers of oad-material, and he could not express too strongly the gratitude f the Ministry of Transport and of the Road Research Board for he whole-hearted co-operation which they had afforded in dealing ith the problem in question.

Mr. T. PEIRSON FRANK remarked that the Paper stated:—"A Mr. Frank. ieasuring instrument, however, can at the best only give a numerical alue." He would submit that the machine could do a little more han that, and thought that the words "fair comparative" might be dded, so that the sentence would imply that the machine in question ould "give a fair comparative numerical value." He suggested hat the machine enabled an engineer not only to compare one ection of a road with another, probably under somewhat similar limatic conditions when the lengths were near together, but also to ompare the same section of road at different times during an xtended period, so that it should be even more useful than might e gathered from the introductory portion of the Paper.

The Authors stated that the ideal road-surface would have haracteristics similar to those shown by curve No. 1 of *Fig. 3*, and dded, "but road-engineers require to know how far they can let an therwise satisfactory surface deteriorate". He thought the Authors ould agree that the deterioration referred to was not disintegration ut deterioration from the point of view of skidding tendencies, due robably in many instances to temperature-changes, sometimes alled hardening-out or rolling-out of the road-surface. He wondered hether some of the excellent surfaces in the Highlands of Scotland

Mr. Frank. were not due in some measure to the fact that they were not subjecte to extremes of temperature such as were experienced in the south c England. He believed that the British Standard Specificatio permitted the use of varying percentages of bitumen so as to su different climatic conditions. When he had been located a Plymouth, he had had a number of experiments made to try to get a safe a bituminous mixture as was conveniently possible according t the temperatures there prevailing.

He believed that he was right in saying that the particular roa referred to on p. 450 as giving a very low sideways-force coefficien was by no means in common use, and that the same remark applie to the old compressed rock-asphalt surface mentioned in Table II He thought that such low coefficients could almost be disregarded s far as present-day practice was concerned. It would appear tha the fifth surface mentioned in Table II would come first and th fourth would come second as to quality. He would like to sugges that tests should be made on bare and on treated wood paving.

He understood from Dr. Stradling's remarks that the sideways force coefficient would be lowest immediately after a slight showe which had followed a long spell of fine weather. That being so, h suggested that motor-vehicle designers should make arrangement to collect some of their "trade wastes"—oil, carbon, and othe products discharged from the exhaust.

The last part of the Paper mentioned the importance of the sitin and planning of roads. Roads were usually constructed with camber, which did not provide the safest and most satisfactor surface upon which vehicles could travel. On such a cambered roa it was sometimes inconvenient to drive near to the curb, particularl on the outside of a bend, when the tendency to side-slip was increase and the object of the driver in general was to travel on the crown the road. It might be safer, and probably more economical, if ne arterial roads were laid out so that the vehicle was always travellin on a suitable cross-fall, and not on a barrelled road-surface. Th cost of drainage-systems might be reduced, and driving, especially night, would be made a little more comfortable and convenient that type of road were more generally adopted.

Mr. Bailey. Mr. T. H. Bailey remarked that the selection of the best materia for road-construction and repairs, and especially for non-sk carpeting, was of great importance. In recent years many product claimed to be non-skid, had been put on the market. The bindi materials for those preparations were in many cases similar, but th success of the non-skid carpet depended much more on the quali of the aggregate used. It was essential that the stone should be of high crushing strength and of a coarse-grained fracture. In ma

:ases the stone used was of a low crushing strength and not of a coarse-grained fracture; in time such stone became pulverized ınder the weight of the traffic, and eventually formed a smooth, ;reacherous surface which also often became greasy. If the carpet ısed was of a fine-grained fracture, the stone became polished under ;raffic and tended to become slippery. Dolerite-olivine granite was ı satisfactory stone for the purpose; typical samples had a crushing-strength of 14·6 tons per square inch, and the grain of the stone was ;oarse. The grading of the aggregate should be regulated according ;o the conditions which it had to fulfil. For re-surfacing roads vhich had become slippery owing to the poor quality of the materials vith which they had originally been laid, a coat of carpeting com-›osed of aggregate ranging from $\frac{3}{4}$-inch down to $\frac{1}{8}$-inch chippings, vith a certain amount of dust introduced as filler, had been found to ›e satisfactory, and to retain its non-skid properties after years of ;raffic. For the reconstruction of worn roads a carpet approxi-nately $1\frac{1}{2}$ inch thick, composed of $1\frac{1}{4}$-inch to $\frac{1}{8}$-inch aggregate, with ;he requisite quantity of dust introduced as a filler, had given ›xcellent results. The roads had remained non-skid for motor ;raffic, horses and cattle, and it had not been necessary to tar-spray ;hem since they had been laid. A point which was often overlooked vith regard to non-skid carpeting was the colour of the aggregate ısed. If it was of a dark colour, the road-surface always remained lark, which was detrimental to night-driving. A carpeting laid vith the stone to which he had referred, after being subjected to ;raffic for approximately 6 months, assumed the original grey-green ;olour of the granite, and that fact considerably added to the safety ›f night driving. Mr. Bailey.

Mr. W. J. Hadfield expressed his appreciation of the way in which Dr. Stradling had brought about collaboration between the ›ractical engineer and the scientist. Mr. Hadfield.

Referring to the subject of road-accidents, Mr. Hadfield was very ;lad that attention had been drawn to the small proportion of road-ıccidents attended with fatal results which took place owing to lefects in the road-surface; that was, however, no reason why ›ndeavours to obtain a safe road-surface should be relaxed. The ›auses of accidents should be removed, and the road should be ıbsolutely safe.

The machine described in the Paper enabled the engineer to neasure the slipperiness of a road-surface in definite units. Through he kindness of Dr. Stradling, the machine had been sent to Sheffield 'or a time, and Mr. Hadfield, speaking as a practical man who had ın idea of the condition of his roads, said that the tests made with he machine had confirmed his own views on the roads tested; in

Mr. Hadfield. consequence, he had a good deal of confidence in the machine. Wha[t] he was afraid of, however, was that if a standard of safety expresse[d] as the sideways-force coefficient were set up, it might prove to be [a] two-edged sword, and engineers might one day find themselve[s] asked questions in court about the machine and whether th[e] safety-point had been reached. At the present moment n[o] safety-point had been specified, but by the time the machine was i[n] common use such a point would have been laid down.

A great deal depended not only on the construction of the roa[d] and on its condition from a structural point of view, but also on it[s] condition from the point of view of cleanliness. It would b[e] possible, as the Authors had said, to have a road which when clean, was quite safe, but when dirty was far from safe. H[e] had never regarded cleansing as being a very interesting branc[h] of road-work, but it was very important, and, where a good roa[d] existed, it was the engineer's business to keep it clean; that was [a] condition of road-safety which was not sufficiently considered.

Professor Clements. Professor R. G. H. Clements remarked that although the percent-age of accidents which could fairly be attributed to the condition o[f] the road-surface at the time was now so low as 1·3, that did no[t] absolve the engineer from dealing with the serious problem, whic[h] fortunately he always did keep before him, of making all efforts t[o] reduce that percentage still further. The significant feature of th[e] Paper was that a number was now available which could be arrive[d] at in a certain manner, had a definite scientific quality, and did i[n] fact give a close index of the actual surface-condition of the road a[t] the time and under the conditions of the test. He was a little sorr[y] that no attempt had been made, on the basis of the numbers obtained to classify road-surfaces into groups for the guidance of road engineers. There appeared to be three clear types: (1) those i[n] which the sideways-force coefficient was high, slightly smaller than 1 whether the surface were wet or dry; (2) those in which the co-efficient was high when the road-surface was dry, but fell to [a] dangerously low value when the surface was lubricated; (3) thos[e] possibly a very small group, in which the surface whether wet or dr[y] had low coefficients. It would be helpful for future surface-con-struction if some guidance could be given in regard to those thre[e] conditions. It was by the engineer attacking those conditions whic[h] he knew to be defective, and ascertaining the precise nature of th[e] fault or defect, that information could best be provided and progre[ss] made.

It was stated in the Paper that the maximum speed at which tes[ts] had been made was approximately 30 miles per hour, which was th[e] safe limiting condition of the present machine. The extension [o]

he measurement of the sideways-force coefficient to higher speeds was, he thought, of great importance, because it was at those higher speeds that the most critical condition arose. Professor Clements.

One part of the Paper was of special importance, as it opened up a parallel line of investigation, namely, that envisaged by the work of Dr. Saal. The alteration from the dry surface which was safe and gave a high coefficient to the wet surface which gave a low coefficient was due simply to the interposition of a third medium, the lubricating film. The laboratory determination of the characteristics of the film which was interposed between the wheel and the surface of the road was probably a most fruitful line of investigation, together with the measurement or approximation of the quality and the nature of the roughness of the road-surface at a given time with a measurement, if possible, of texture itself. With that there was bound up the film tension of the liquid or lubricating medium, in relation to the surface-tension of the stone or composite material forming the road-crust. The investigation called for by the authors, namely, the extended use of their piece of scientific apparatus and the analysis of the data which could be obtained by its use under actual service conditions throughout the country, should be paralleled by supplementary investigation of the scientific conditions which arose at the interface between the wheel and the road.

Mr. W. P. Robinson, considering the matter from a severely practical point of view, ventured to suggest that the Treasury should at the outset purchase five machines, one to be placed in each of the five highway-divisions of the country and to be available for hiring out by the highway-authorities at a daily rental. He was afraid it would be very difficult for the highway-engineers to persuade their authorities to provide separate machines for their own use, when possibly during the summer there would be no skidding tests to be done. He had been driving vehicles for 40 years, and had had only two skids during the whole of that time, one of which was on a snow-bound road and the other on an ice-bound road; he did not think the problem of skidding was so important as the problem of being able to measure when a road was due for repair. Skidding was probably partly due to the want of repair, and if a method could be developed to determine when a road required resurfacing or repair he thought the problem of skidding would automatically be dealt with. Mr. Robinson.

The Authors had referred to the argument regarding the merits of a "sandpaper" finish and a rough surface. It was suggested that when a film was formed there was more liability to skid on a smooth surface, but did it follow that a rough surface would get rid of that film? Some engineers found that a rough surface provided a

Mr. Robinson. receptacle for water, grease, and so on, and thus increased the liability to skid. There were points on both sides, and practical engineers looked to scientists to use the measuring instrument which had been provided to find out the facts, and thence to deduce what was the best type of surface from the point of view of durability and of reduced liability to give rise to skidding.

Mr. Marriott. Mr. T. G. MARRIOTT said that in his opinion the particular aspect of the road problem which was under discussion had its origin about 20 years ago. At that time road-manufacturers, of whom he was one, were troubled with corrugation, which arose from the following cause. The roads of the country were passing from waterbound macadam to the bituminous surface; in the process of transition mixtures of insufficient stability were used, and surfaces were imposed on foundations which were insufficient, so that the chief difficulty met with was foundation-weakness and corrugation. He mentioned that because he thought that the various road problems were complementary. The difficulty with regard to foundations was quickly removed by the developments in the use of concrete, but the problem of corrugation had then to be faced owing to the rapid transformation from the water-bound to the bituminous type of road. There was such anxiety to avoid disintegration that too much bituminous matter was put into the surface, and that caused the corrugation. At that period there still remained a large volume of horse-drawn steel-tired slow traffic, and the transition between the two types of traffic created a problem which had not yet been finally solved, because there still remained large areas of old-fashioned pavings put down at the period to which he referred which were not yet worn out, but had given rise to the problem of slipperiness.

There were two schools of thought with regard to the prevention of slipperiness, those who advocated the "sandpaper" finish and those who advocated the rough-textured surface. The leading advocate of the "sandpaper" finish was Professor R. A. Moyer, but unfortunately Professor Moyer's data were based entirely on American experience. Mr. Marriott knew something about the conditions in America. In the winter months in any of the big cities of America rain might fall on 20 consecutive days, but the pavements never failed to dry out each day. The problem in England was different; the pavements in London often remained wet for long periods, while in Glasgow they hardly ever dried out from October until March or April. As the dry atmosphere in America caused the pavements to dry out so quickly, Professor Moyer thought that with modern high-speed high-braking-power vehicles a smooth surface was satisfactory. So far at any rate a

reat Britain was concerned, Mr. Marriott disagreed with that view, Mr. Marriott. ecause of the difficulties caused by the moisture film, which in ondon was accompanied by soot and was therefore particularly ffective as a lubricant. In view of the filth which fell on the London treets a smooth surface was most dangerous for modern high-speed raffic. He thought that by following the British Standard Specifica-ions for bituminous work the new roads would be found to be easonably satisfactory. In view of that, and with the aid of the Iinistry of Transport, he believed that the problem of the old-ashioned smooth type of pavement was being coped with gradually ut effectively. As Mr. Cook had indicated, a system was slowly eing evolved by which it would be possible to superimpose on any ype of surface a pavement so graded that with reasonable conditions f climate and traffic it would afford a satisfactory tire-grip for ehicles.

Mr. H. V. OVERFIELD said that he believed that most skidding was Mr. Overfield. ue to careless driving. Roads should be made as foolproof as ossible, but reasonable care was to be expected from drivers. He nagined that wet wood-blocks and compressed asphalt, especially ı industrial towns and on damp and foggy days, provided probably ıe most slippery surfaces, but even those surfaces were not quite so ad after a heavy fall of rain.

The results given in the Paper of the road-tests under wet con-itions were of the kind that might have been expected, but it would e of interest if the Authors would say whether the roads under test ere merely damp or whether they had been washed by heavy rain. [e thought that before figures were taken as enabling the value of ne surface to be compared with that of another, the road under test iould be perfectly true ; otherwise the effects of impact might upset ıe frictional resistance. The results obtained under dry conditions ere very surprising, in that the sideways-force coefficients were so ery high for all normal clean surfaces. If those figures were the ıly standard by which the road-surfaces were to be judged, some ıerished theories would probably be upset. He did not think, owever, that the Authors would claim that those figures did con-itute the final standard. For example, he had heard it whispered ıat one of the roads that gave very good results broke up soon after ıe test. As an instance of that upsetting of theories, the advantages aimed for lake asphalt (which contained mineral matter in its ıtive state) over the residual bitumens in asphalt cements, ıd for the so-called "sandpaper" finishes of the fine asphalt ppings which were admittedly giving very excellent results, would of no effect. He himself still thought that both those materials ere preferable to many others in road-surfaces.

Mr. Overfield. The decrease of the coefficient as the speed increased was im portant, and it was possible that that was partly due to the rapi variations in pressure and contact between the tire and the road The pneumatic tire was subject to so many unknown conditions a high speed that he wondered whether the Authors would consider i worth while to make tests with an iron tire or a stiff solid rubber tire At first sight it might seem a waste of time even to suggest workin with iron tires, when their use on the roads was rapidly coming t an end, but he had discussed the point with many horse-owners, an it was claimed quite seriously that horses shod with iron shoe travelled better and more surely on wet roads. The horse-owner also preferred the "sandpaper" finish, possibly because the surfac was rather softer than that of many of the harder asphalts. The certainly disliked the hard polished surface in worn granite-dresse roads, and much preferred gravel or quartzite coverings, which wer relatively friable. Another curious fact which might be mentione was that road-rollers with steel wheels had a much better grip tha those with cast-iron wheels. With horses and road-rollers, howeve the iron or steel came into contact with the road at very low speed and perhaps even the suggestions of the horse-owners were no inconsistent with the figures in Table II, where the coefficients wer still quite high at a speed of 5 miles per hour.

With regard to the question of surface-texture, he thought it wa admitted that a high degree of frictional resistance was required, bu it should not be obtained at the expense of other requirements of th road, and that was where the judgement of the practical man wa required. The surface should be as smooth as possible for cleanline and low tractive resistance. Both were fundamental requirement and a balance had to be struck between the roughness required f frictional resistance and the smoothness which was desirable f cleanliness, especially in towns. Clean road-surfaces were require to reduce the effects of lubricating films, but during rainfall on ve flat roads water would form thick films. Good drainage of t surface was necessary, and that called for sufficient but not excessi cross-fall. In that connection attention might be called to certa new road-paving systems where parts of the surface of the bloc stood above the rest. For example, the road in the Mers tunnel had a surface formed of cast-iron blocks with diamon shaped projections. From such a surface water would drain aw in the grooves, leaving the projections almost dry, and that mig help to prevent the formation of film. Personally, he thought inconceivable that a pneumatic tire could skid on such a surfac because the diamond-shaped projections were forced into the rubb and formed a mechanical bond. An attempt had been made

tain the same result by making blocks of a fairly hard asphalt with Mr. Overfield. grooved pattern on the surface. Roads made with those blocks ied very quickly, and even during rainfall the surface remained irly free of water. He had been told by those who had charge of ich roads that they remained very clean under all conditions, but was not prepared to say that they were practicable for extensive e, on account of their cost.

Skidding was probably due more often to the defective layout of ads than to defects in the surface-texture. Excessive camber and idden changes in the curvature gave rise to large unbalanced lateral rces. Many curves were deceptive, and an inattentive driver ight find himself travelling too fast when he reached the curve. he research work described in the Paper might, he thought, be ipplemented by a detailed examination of conditions on curves, id he would suggest that the experimental machine described by ie Authors should be fitted with accelerometers, by means of which ie centrifugal forces could be recorded, together with the sideways-sistance coefficients. He thought that if the reconstruction of ie roads were accelerated and carried out on proper engineering ies, the problem of the slippery road would be solved.

Mr. F. G. TURNER remarked that his daily work brought him very Mr. Turner. uch in contact with the Authors, as the great majority of the tests hich had been done by them and their staff with the machine scribed in the Paper had been carried out at his request. It had ierefore been agreed that he should wait until the end of the dis-ission and should then deal with any questions which had been ised with regard to any of the roads referred to in the Paper. Very w points of that kind had been made, but Mr. Frank had referred the road which was described on p. 450 as being very slippery. hat was a road which had been brought to notice as being slippery, id immediately afterwards it was treated and made safe; it as of a special new type of construction which proved unsatisfactory, ilure being largely due to unsuitable weather-conditions during nstruction. The suggestion had been made in the discussion that ood blocks should be tested. The figures given in the Paper ferred only to typical examples of roads, and a number of tests id been made on wood blocks.

Mr. Overfield had asked whether the tests were made on roads at were damp or on roads that had been washed by heavy rain. iat naturally depended on the circumstances; the machine had be sent from its headquarters to the road where the test was to be ade. Whenever possible the machine would get to the road soon ter the rain had started, and in that case the road would only be mp; but occasionally the rain had been heavy enough to wash

Mr. Turner.

the road, and then that factor was noted and allowed for when th results were considered. Mr. Overfield had referred to a rumou that one of the roads that gave very good results had broken up soo after the test; Mr. Turner had not heard of that rumour.

While the Paper was being read he had heard someone whispe "Why a smooth tire?" It might be helpful, therefore, to refer t the way in which he had always regarded the matter. The coefficien was measured between the tire and the road, and the result mus therefore depend, and did depend to an appreciable extent, on th condition of the tire. While the test was being made, the wheel wa partly skidding and partly revolving, and the wear on the tire wa therefore very heavy. He thought he was right in saying tha under normal conditions of test on a wet road the life of the tire wa about 30 miles. The consequence was that if a treaded tire was use the change in it would be so rapid that it would not be possible t compare any one test with another, and a smooth tire was used fo that reason.

It might also be of interest to mention that the tests showed tha the lowest figures, with which all those responsible for roads wer concerned, were always obtained when a road was tested while i was getting wet, and that was particularly the case after a prolonge dry spell. If reliance were going to be placed on rain, as distinc from artificial watering, to give a wet road, a very definite limit wa placed on the radius of action of the machine; the maximum figur would probably be about 20 or 30 miles. That was one of th reasons why it was desirable to increase the number of machines.

Professor Clements had referred to the question of the maximun speed, and had suggested that the tests had been limited to 30 mile per hour on the grounds of safety. Mr. Turner thought the limitin factor was rather the power required to drive the machine; th wheel was partially locked, so that the frictional resistance wa approximately at its maximum value, and the power required t drive the machine at 30 miles per hour was as much as could b obtained.

Mr. Forty.

*** Mr. F. J. Forty observed that further explanation of certai points regarding the interesting devices developed by the Autho would be welcome. Firstly, in the Paper no account was taken c gyroscopic effect in the case of the motor-cycle and sidecar machine it would appear to influence the observed results, and would depen upon the speed of the vehicle. Secondly, there would be trans mission of a sideways force to the main frame, which would appea

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*** This and the succeeding contributions were submitted i writing.—Sec. Inst. C.E.

tend to divert the motor-cycle from a straight path. The natural Mr. Forty.
tion of the driver was to correct that tendency, and the human
ement, therefore, would obtrude in the case of different drivers.
irdly, was it thought that the camber of the road-surface would
troduce a variable factor in comparing different surfaces?
ssibly some device had been incorporated for counteracting that
fect. It would be interesting to know whether the two latter
ctors had been found to have any effect on the ease of control of
e machine.

Mr. G. H. Hodgson observed that the Paper had emphasized the Mr. Hodgson.
fluence exerted on the finished surface of the road by two main
ctors, namely, the lubricating film, and the roughness or other
tributes of the surface tending to prevent film-formation.
timately connected with those two factors was the choice of the
ck from which the chippings were produced. Chippings should
ve a rough fracture, should be able to stand up to heavy load with-
t crushing, and should have a good resistance to abrasion. Under
ar, the fine mineral matter produced should be coarsely crystalline,
d not an impalpable powder. From the study of plaster casts from
ads surface-dressed with chippings, it could be seen that such a
rface was excellent to prevent film-formation, as much of the
terial forming the lubricating film could pass away between the
ippings to the channels, so that the top of the chippings could
e the necessary frictional resistance.

Mr. F. W. Vallé-Jones observed that the test-results given in the Mr. Vallé-Jones.
per did not include figures for iron roads or wood-block paving,
ich would have been particularly interesting. On account of the
all difference found between the frictional resistance of hot-
halt surfacing treated with pre-coated chippings at the time of
ing and after several years of wear, it was evident that the road
ted was taking comparatively light traffic. It might be argued
t the road chosen for those tests was a good one to be taken as a
ndard, but it would be unfair to judge different surfacings on those
es unless there were uniformity in conditions of traffic and in the
s of the pavements. Whilst it would be difficult entirely to
minate the lubricating film which was deposited on roads, it would
possible to reduce it very greatly by more frequent scavenging.
m the point of view of cleanliness and ease of scavenging the iron
d could not be surpassed. The hot-asphalt carpeting treated
h pre-coated chippings used as a surface veneer failed when
jected to heavy horse-drawn steel-tired traffic. The protruding
ppings were ground gradually to powder, and in a comparatively
rt time the road might be rendered useless from a non-skid
ndpoint. For rubber-tired traffic that type of road had been

Mr. Vallé-Jones.

satisfactory so far, but it had yet to be proved whether it wou remain non-skid for any reasonable length of time, and exampl which had "faced up" in a month or two under heavy traffic we not uncommon. The lubricating film which was formed by ra with solid matter did not, in his opinion, materially affect the no skid value of a rough road, and its effect on roads properly scaveng would be reduced to a negligible quantity. The same lubricati film on a smooth road, however, produced a very dangerous surfac The index of the value of any non-skid road was best measured b its tendency to polish, which could be better measured in t laboratory than on the road, the road-specimen being treated as stationary surface and a piece of solid rubber rubbed over it at a give rate either backwards and forwards or in one direction only, a simp but effective test.

One of the speakers had referred to granite chippings having crushing strength of approximately 14 tons per square inch, whic he stated, had given remarkable results in making a non-skid roa Such chippings could only be used for lightly-trafficked road Suitable chippings for general work should have a crushing strengt of not less than 20 tons per square inch, and it was possible i England to obtain chippings having a crushing strength of 25 to per square inch, which were ideal for use in surface-dressing.

It was remarkable that the sideways-force coefficient had bee found to be much less in wet weather during summer than in w weather during winter, and in the Paper no reason appeared to b given for that effect. Would it not indicate that there was a tendenc for the binder to exude and play a part in lubricating the surfac and that the proportion of binder should be reduced to a minimu in order to make roads safe ? As the sideways-force coefficient wa reduced by approximately 50 per cent. when the speed was increas from 5 miles per hour to 30 miles per hour, apprehension might b felt as to what would be the value of that coefficient at 60 miles p hour. He had often drawn attention to the fact that London roa were not safe at speeds of more than 20 miles per hour, and t results given in the Tables confirmed that statement. Were futu tests to be limited to 30 miles per hour ?

The provision of non-skid roads near main goods-stations present a difficult problem, as the heavy horse-drawn steel-tired traf caused considerable damage to any type of thin veneer. Whil such roads were safe for motor-traffic they could not be said to b safe for horse-drawn traffic. The frictional resistance on such roa might change from month to month on account of the continu grinding of the chippings. On such surfaces horses could slip ev in dry weather. The testing of the frictional resistance of the vario

Mr. Vallé-Jones.

pes of roads carried out by the Ministry of Transport had esumably been carried out with the vehicle travelling in a straight e, but there could be little doubt that, whilst most surfaces might safe under those conditions, they failed when vehicles left the aight course.

Mr. Walker.

Mr. J. H. WALKER observed that the majority of motorists would ssify road-crusts having untreated surfaces roughly into the lowing three classes: (1) non-skid crusts requiring neither the inkling of sand or gravel in wet weather, nor the periodical perposition of non-skid carpets; (2) crusts which when new were d-proof, but which sooner or later became more or less slippery; crusts which initially had slippery surfaces. Class (1) included granite setts, where the granite itself was of a non-slippery ture; (*b*) water-bound macadam, free from any muddy matrix; concrete, with a surface-aggregate consisting chiefly of large nite macadam in sizes ranging from 1½ to 2½ or 3 inches. Class (2) luded (*a*) macadam, blinded with fine material, such as old road-apings, which in wet weather could work to the surface to form a n layer of mud; (*b*) tar-macadam or synthetic asphalt, out of ich in hot weather the tar or bitumen could "bleed" to the face; (*c*) concrete road-crusts with a small-sized surface-aggre-e, from ¼ to ¾ inch. Class (3) included non-gritted wood-block ving and rock asphalt. Road-crusts of class (1) were but a small centage of the total mileage of roads, as granite setts laid on ncrete foundations were very expensive, and the virtues of large nite aggregate in the surface of concrete roads were little known. usts of classes (2) and (3) were too often legacies for which the intenance-engineer was by no means grateful. Such crusts uired non-skid carpets imposed upon them, which had to be ewed periodically. So long as road-crusts with slippery surfaces l to be maintained, and consequently had to be covered over with ewable non-slippery carpets, so long would the need exist for such levice as that described and recommended in the Paper.

In Table II a sideways-force coefficient of 0·50 was given for old nent-concrete roads in wet weather. No doubt that value had n obtained on a polished surface containing small aggregate. would be interesting to have that experiment repeated on the ginal and untreated surface of a 10-year-old road, surfaced with ge aggregate. Such a road could be chosen from 10 miles of urfaced non-skid roads in Greenwich, from many such roads in Docks of the Port of London Authority, from 6-year-old surfaces the Cardiff streets, or from similarly surfaced streets 60 years old Edinburgh. A suitable construction for a non-skid concrete road nsisted merely of anchoring 6 inches of non-reinforced 6-to-1

Mr. Walker. ballast concrete, in 10-foot bays, on to a roughly-graded formatic and topping the unset concrete with a layer 3 inches thick of a 6-tc mix of large-aggregate concrete, taking care that all joints we properly interlocked. In many cases such surfaces were spray with a mixture of tar and bitumen at intervals of a year or mo without giving cause for any complaints of slipperiness. The 19 report of the experiments made by the Ministry of Transport stat that sections of such roads had been laid in various places. Th were not, however, anchored to the ground as were those that ha proved themselves so successful during the past 60 years or mor Instead, they were laid as freely-moving slabs on a 3-inch bed rolled ashes covered with a layer of brown paper. That provisio for free movement of the slabs might be thought to be very ba practice. Whilst no useful results were likely to be obtained fro such recent experiments until 10 years or so had elapsed, there we in Great Britain many miles of proved roads of any age up to 17 year and also roads 60 years old or more, which could be examined wi regard to their non-skid properties, all-round efficiency, and cheapne of construction.

He would suggest that the proper cure for slippery road-crusts w to replace them as quickly and economically as possible with no slippery crusts having great compressive strength in all weather as was the case with concrete roads when properly constructed as to give a perfect unwarped running surface. In the meantim but merely as a temporary measure, all surfaces known to be slipper should be covered up with non-skid carpets, notwithstanding tl first and repeated costs of doing so. If the above suggestions we acted upon, the excellent device recommended by the Autho should in time become unnecessary.

Mr. Batson. Mr. Batson, in a preliminary oral reply, said that Mr. Turner ha mentioned that the reason for the use of a smooth tire on the te vehicle was the change which would have occurred on a tread normal design due to wear, but there was also another reason, namel that the type of tread had an important effect on the values obtaine If treaded tires had been used it would therefore always have be necessary to have used exactly the same tread-pattern, and tl results would have been peculiar to that tread-pattern, even if we had not taken place. That might explain some of the results foun by Mr. King and referred to in the Paper, where a difference w found between sideways-slipping and straight-on skidding ; tho differences were due to the type of treads employed. If Mr. Ki had used treads of a different design he might have obtain a different comparison.

Several speakers had referred to the results given in Table I

should be emphasized that those given were only typical values; Mr. Batson. echnical paper would be published in which the whole of the results ould be set forth, and that paper would deal with Mr. Overfield's estion with regard to the effect of rainfall on the results obtained. Professor Clements divided the test results into three zones, and the last zone put those of the surfaces which gave low sideways- ce coefficients whether they were wet or dry. The Authors' perience was that they had been able to obtain low values on dry rfaces only when those surfaces were covered with loose material, loose material acting as a kind of ball-bearing. Professor ements also referred to the importance of further work on the ricating film, in addition to the collection of results by means of motor-cycle and sidecar. Work on that aspect was being actively rsued at the Road Research Laboratory, and it was hoped in the urse of a short time to have some further information on the oject.

The AUTHORS, in completing their reply, stated that they The Authors. preciated the kind way in which the Paper had been received and many helpful suggestions which had been made.

They agreed to the suggestion put forward by Mr. T. Peirson Frank t the motor-cycle and sidecar skidding-machine would give a air comparative numerical value" and also that the references deterioration made in the Paper related to deterioration in regard skidding tendencies. They could not, however, endorse the view t "low coefficients could almost be disregarded so far as present- practice was concerned." Some types of road-construction ich they had tested had shown rapid deterioration after 6 months' , although the value of 0·7 had been obtained shortly after com- tion. They would agree, however, that the methods suggested the British Standards Institution, if carried out under careful ervision, would give a comparatively long skid-free life.

There appeared to be some misunderstanding as to the function of motor-cycle and sidecar. It had not been designed to take into ount vehicle-characteristics other than those of the tire, or to l with the human element or measure the centrifugal force at ves, but was solely a mechanical device for determining the tional force resisting skidding between the tire and the road- face under normal speeds and weather-conditions. It had been nd that the camber of the road did not affect the results obtained. sideways force from the sidecar-wheel was ultimately resisted the friction between the rear wheel of the motor-cycle and the l, and when a test was carried out the observer rode on the on in order to provide the maximum adhesion of the rear wheel. lier work on the subject carried out at speeds below 5 miles per

The Authors. hour did not show low coefficients even on samples cut from roa which were known, from practical experience, to be dangerous fro the point of view of skidding. It was not until tests were carrie out with the sidecar apparatus that the large reduction in coefficien with speed on some surfaces was demonstrated, and the resul obtained were brought into line with the general experience of roa users. The maximum speed of test with the apparatus depende upon the frictional resistance of the surface, and with the prese machine 30–35 miles per hour could usually be obtained. A ne machine, having a more powerful engine, was under constructio and higher speeds should be possible when it was brought into use

Mr. Vallé-Jones suggested that the small lowering of the friction resistance of the hot-asphalt surface after 4 years' service (given Table II of the Paper) was evidently due to the road having tak comparatively light traffic. The section of road from which tho results were obtained was on the Kingston By-Pass, which carried large volume of traffic.

It was remarked that no reason had been given in the Paper account for the fact that the sideways-force coefficient was found be much less in wet weather in summer than in wet weather winter. That matter was under investigation at the Road Resear Laboratory, but it was believed that one or more of the followi factors might be responsible for the effect obtained :—

(*a*) Higher temperatures in summer caused exudation of the bind and polishing of the surface. In winter, owing to the colder weath that polished layer would be removed by abrasion.

(*b*) In summer, rain-water was evaporated quickly, leaving t detritus on the surface, while in winter, owing to lower temperatu and higher humidities, the rain washed the detritus into the gutt and left a comparatively clean surface.

(*c*) In summer, vehicle-tires were at a higher temperature than winter and helped the polishing effect on the surface. In summ also, oil-leakage from vehicles was more pronounced.

In dealing with concrete surfaces, Mr. J. H. Walker stat that many such surfaces were sprayed with a mixture of tar a bitumen at intervals of a year or more without giving cause for a complaints of slipperiness. It was assumed that chippings w afterwards spread and rolled. The measurements that the Auth had made on concrete roads led to the belief that no such treatm was necessary to ensure a non-skid surface.

Several speakers, notably Mr. Hadfield and Mr. Overfie emphasized the importance of cleanliness of the surface, and w those remarks the Authors were in complete agreement.

ORDINARY MEETING.

10 March, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Author.

Paper No. 5056.

"The Construction of the Mersey Tunnel."

By David Anderson, B.Sc., M. Inst. C.E.

TABLE OF CONTENTS.

History.

More than 130 years ago suggestions were put forward for constructing a tunnel under the Mersey, and all through the nineteenth century efforts were made from time to time to achieve some better means of communication between Liverpool and Birkenhead than that afforded by ferries. During the Victorian era railways gradually became more important than roads, and the first scheme to come to fruition was a railway-tunnel. The Mersey Railway, opened in 1885, showed that none of the many difficulties in the construction of such a work was insurmountable, even with the methods of tunnelling in use at that time, while during its construction much

valuable information was obtained about the real nature of the problems existing below the Mersey.

Increasing population, and the enormous development of road-transport which followed the introduction of the internal-combustion engine, made those interested in the prosperity of the district feel more and more that existing facilities were inadequate. Various schemes were put forward, notably that by Mr. C. W. Mallins for a tube-railway system, whilst for many years Sir William Forwood persistently advocated a road-tunnel as the solution of the problem. The financial side of the question was very important, and it was felt eventually that a complete survey of the possibilities should be made ; this survey should take into consideration the requirements of through traffic as well as those of local traffic, and should also consider the relative advantages of a bridge and a tunnel.

Accordingly, a joint Committee was appointed in 1922, with Sir Archibald Salvidge as Chairman. This committee included representatives of Liverpool, Birkenhead, Bootle and Wallasey. The Committee asked the late Sir Maurice Fitzmaurice, Mr. (now Sir) Basil Mott, and the late Mr. John A. Brodie, Past Presidents Inst. C.E., to make a joint report on these alternatives. This was submitted after a thorough study of the position. The report was strongly in favour of a tunnel. The high level necessary for a bridge, owing to river traffic, and the very long approaches over a thickly populated area, made the estimated cost of a bridge, with the proposed span of 2,300 feet, considerably higher than that of a tunnel. Even with this span, both main piers would have been in the river, with consequent restriction of the waterway.

In September, 1923, the Joint Committee adopted the tunnel scheme as recommended. After much negotiation between the various authorities concerned, during which the authorities of Wallasey and Bootle withdrew from the scheme and the original idea of running trams through the tunnel was abandoned, a Bill was brought before Parliament and was passed in August, 1925. Under the terms of the Act, a Joint Committee of Liverpool and Birkenhead was set up. The first chairman was Sir Archibald Salvidge who, on his death in December, 1928, was succeeded by the present Chairman, Sir Thomas White. Sir Basil Mott was appointed Consulting Engineer for the work, Mr. Brodie being associated with him.

Work was started on the first shaft in December, 1925, after an inaugural ceremony at which Her Royal Highness Princess Mary turned on the compressed-air-supply for the pneumatic drills. The position for the under-river tunnel was now definitely fixed, but the positions of the various entrances were altered several times. Amending Bills passed in 1927 and 1928 were the results of the

decisions reached, and the general lay-out was brought into its final form described in the Paper. The works were estimated to cost £4,727,000 and the land £495,000, making a total of £5,222,000. This amount was considerably exceeded for the reasons explained later. The tunnel was opened to traffic on 18 July, 1934, by His late Majesty King George V.

General Description.

The Mersey tunnel consists of a main tunnel which passes under the river Mersey, and connects Liverpool to Birkenhead, with two branch tunnels, one on each side of the river, running in each case to an entrance near the docks. The main tunnel has a roadway 36 feet wide for four lines of traffic, and each of the branch tunnels has a roadway 19 feet wide to take two lines of traffic. On the Liverpool side, the main tunnel-entrance is at Old Haymarket, and the branch tunnel-entrance is at New Quay. On the Birkenhead side, the main tunnel-entrance is at Chester street, and the branch tunnel-entrance is at Rendel street.

As viewed from the roadway, the upper portion of the main tunnel appears as a semicircular arch, and that of the branch tunnels as a smaller semicircular arch over vertical side walls. Near the two Birkenhead entrances there are short lengths having a flat roof. Actually, the sectional formation varies considerably in different parts of the tunnel to meet special conditions. The under-river portion, 5,204 feet long, is a complete circle of 44 feet internal diameter, constructed of cast-iron rings. The remainder of the main tunnel has a semicircular upper portion, constructed either of cast-iron or of steel ribs and concrete, with a concrete invert. There is a short length over the Mersey Railway with a cast-iron invert conforming to the line of the usual concrete invert; the flat-topped length near the Birkenhead entrance has a roof formed of plate-girders, with concrete side-walls and a concrete invert.

The branch tunnels are constructed either of cast iron, the semi-circle being of 26 feet 6 inches internal diameter, or of steel ribs and concrete with a concrete invert throughout. The flat-topped length is similar in construction to the corresponding length of main tunnel. Throughout the whole length the roadway is carried on a reinforced-concrete slab, and the space below this is used primarily as a duct for the fresh-air supply.

The general lay-out is shown on Fig. 1, Plate 1. There is an open plaza at each entrance, with traffic-controls and architectural features. From the plazas, approach-ramps, constructed in open cut between retaining walls, lead to the tunnel-portals. The main and branch

tunnels unite at junction-chambers cut in the rock and lined with concrete.

The general gradient in the main tunnel is 1 in 30, but there is a 332-foot length of 1 in 20 inside the Haymarket portal. The lowest point of the roadway (148 feet below H.W.L.) is under the river about 4,275 feet from the Haymarket portal, and the main drainage-sump and pumping-station are placed there. Towards Birkenhead the tunnel rises at a gradient of 1 in 300 for about 1,671 feet before steepening to the 1 in 30 gradient which continues to the portal in Chester street. The general gradient in the branch tunnels is 1 in 30, but there is a length of 1 in 40 near the junction-chamber in the Rendel street branch.

The ruling curve for all the tunnels is 500 feet radius, except for one length in the New Quay branch tunnel, which is on a curve of 400 feet radius. The length of the main tunnel, from portal to portal, is 10,620 feet, or from street-level to street-level 11,372 feet. The Birkenhead branch tunnel is 1,654 feet long from the junction-chamber to its portal, and the corresponding length for the Liverpool branch tunnel is 1,561 feet.

Geology.

Almost the whole of the tunnel lies in the Middle Bunter Sandstone. The strata have a general dip towards the east, and a fault on the Liverpool side brings a length of both the main and branch tunnels into the Upper Bunter Sandstone. The upper portion of the tunnel near the entrances leaves the rock and enters the overlying glacial drift and made ground. The surface of the rock forms a valley following approximately the shape of the river-bed, but there is a glacial channel near the Liverpool bank of the river which is lower than the general level. In order to prevent the top of the tunnel leaving the rock at this point, the projected level was lowered, but even in its present position the minimum cover is only about 3 feet. There are numerous fissures leading water down through the rock, and, as would be expected, the general concentration is towards the Liverpool side. Numerous borings were made during the construction of the tunnel, and the general rock-surface was accurately established. It was found that for a considerable distance over the river-length there is a layer of sand and ballast overlying the rock but below the boulder-clay which forms the river-basin. The rock through which the under-river length of tunnel was driven was fairly uniform, but there was an area of broken rock and faulting about 1,200 feet from the Liverpool quay-wall.

Working-Shafts and Pilot-Headings.

Before undertaking the construction of the tunnel to the full diameter, it was decided to drive pilot-tunnels along the proposed line. The advantage of this procedure was that it provided for a full exploration of the strata through which the tunnel was to be driven, and made it possible to carry out any special works found to be necessary for sealing or strengthening the adjacent ground. Fissures or broken rock could be located and dealt with before any large-diameter excavation was undertaken. When the main operation was in progress, the area of exposed ground at the face would be very much reduced, and the full-size tunnel could be broken out at any points desired.

These are well-known advantages, but they were particularly important for the Mersey tunnel where the diameter was very large, the rock cover very small, and a large proportion of the driving subaqueous. The actual conditions which were encountered fully justified the use of pilot-tunnels. The general scheme for the work was to drive towards the centre of the river from a point on each side, and at the same time to drive landwards from these points towards the tunnel-entrances. For this purpose two working sites were chosen, one at George's Dock, Liverpool, and one at Morpeth Branch Dock, Birkenhead. From these sites two working-shafts were sunk.

These shafts, which were the first important part of the constructional work to be carried out, were 21 feet 2½ inches in diameter. They were sunk as permanent shafts, the one at George's Dock to be used later for access, and the other at Morpeth Dock as an emergency exit. The upper lengths, where the foundations of the surrounding buildings might have been endangered, were lined with cast-iron segments. The design of this lining was the same as that used for the station-tunnels of the tube railways in London. The lining was discontinued about 50 feet below ground-level on the Liverpool side, and about 30 feet below ground-level on the Birkenhead side.

Before driving through the water-bearing rock at the lower levels, the sinking was stopped for about 2 months while the rock through which the shafts were to be driven was treated by the François cementation process in order to restrict the inflow of water as much as possible. A number of holes about 2 inches in diameter were drilled around the periphery of the shaft at about 2 feet centres, and cement-grout injected under pressure to fill up any fissures or cavities. In the New Red Sandstone the rock was further treated by the injection of sodium silicate and aluminium sulphate. The injection-pressures used were generally restricted in accordance with

the weight of overlying rock, in order to reduce the risk of uplift. The cementation-process was carried down far enough to form a plug extending 15 or 20 feet below the bases of the shafts.

The finished shafts were nearly 190 feet deep, being carried about 70 feet below the tunnel-level to form drainage-sumps. They were offset from the tunnel-line, and at the required level adits were first driven to reach the main centre-line. The rock here was also treated by cementation, both from the shafts and by drilling and injecting from the surface.

For the river-length of tunnel two pilot-headings were driven along the centre-line of the main tunnel, one vertically below the other. At the same time, a 7-foot drainage-heading was carried forward from the bottom of the Liverpool shaft, sloping upwards at 1 in 500 to meet the lower pilot-heading at its lowest point under the river. Vertical shafts connecting all three headings were driven at intervals. The tunnel-headings were 15 feet wide and 12 feet high, with an arched roof. For the lengths of tunnel under the land, only a single heading of the same dimensions was driven in the lower half of the main tunnel. While exploratory borings and cementation were being carried on from the upper heading, the lower one was carried forward, and vice versa.

For some months after the commencement of work, all excavation was carried out with pneumatic drills and breakers. Progress, however, was found to be very slow, and experiments were made to see if blasting could be carried on without damage or undue disturbance. This was found to be satisfactory, giving greatly increased progress, and the method was generally adopted except in dangerous areas, such as under the glacial channel. The cementation and chemical treatment of the ground was carried forward ahead of the pilot-headings to cover the whole section of the completed tunnel, pipes being driven forward alternately from the top and bottom headings. In spite of the cementation the seepage of water through the rock was very heavy. About 4,200 gallons per minute were pumped out of the Liverpool shaft at one period, but the great bulk of this was from the drainage-heading which was not cemented. On the Birkenhead side the amount of water was only about one-tenth of this, and no bottom drainage-heading was necessary. It was clear that the finished tunnel would have to be given a completely waterproof lining, and on the experience gained it was eventually decided that the continuance of the cementation was no longer justified. This allowed more rapid progress, and a successful junction was made under the river within the contract time of 25 months.

Where the rock was in good condition the headings were left unlined, but timber props or mild-steel T-bar frames were used where

the rock was heavy or broken. A length of about 400 feet of the top heading, situated under the buried channel of the river on the Liverpool side, was circular, and was lined with 11-foot $8\frac{1}{4}$-inch cast-iron rings of tube-railway section. This was done as a safe-guard where the rock cover was known to be very small.

Cast-Iron Lining.

The cast-iron lining was constructed on the usual principle adopted for tube railways and under-river tunnels, but was modified to meet the special conditions existing in the tunnel. The rings were built up of flanged segments, bolted longitudinally and circumferentially. They were designed to be strong enough to withstand in the first place the stresses due to their own weight during erection, and afterwards the pressure of the water in the rock. The ring was completed by the insertion of one or more wedge-shaped keys.

In large tunnels it is usual to roll alternate rings axially half the length of a segment so that each ring breaks joint with the next. In the Mersey tunnel, however, the upper half of the lining was erected first, and a continuous straight joint resulted along the horizontal axis of the tunnel. To allow for this, whilst retaining the break of joint for the remainder of the circumference, special making-up segments were used in alternate rings, and there were two keys, one at the soffit and one at the invert. The circular cast-iron sections for the main tunnels are shown in Figs. 2, Plate 1. Two widths of ring were used, one of 18 inches for the "break-ups" and lengths of tunnel requiring special strength, and one of 24 inches for the general run of the tunnel.

The depth of the flange is 1 foot $1\frac{1}{2}$ inch, with an internal diameter of 44 feet and an external diameter of 46 feet 3 inches. The bolts are $1\frac{1}{2}$ inch in diameter, and for the circular flanges were evenly spaced round the tunnel on two pitch-circles, one 45 feet 5 inches in diameter and the other 44 feet 8 inches in diameter, there being four bolts in each flange of a full-length segment. In the horizontal joints there are five bolts for the 24-inch segments, and three for the 18-inch segments. The thickness of the iron is $1\frac{1}{2}$ inch on the skin, the flanges tapering from $2\frac{1}{2}$ inches to $1\frac{1}{2}$ inch. The bolt-holes are cored in the casting, and there are two grout-holes per segment which are tapped and afterwards fitted with screwed plugs. All four flanges of each segment are planed on the contact-surfaces, and a recess forming the caulking-groove between the segments is also planed. The keys used are solid cast-iron blocks, cored to take the circumferential bolts. The segments next to the keys are specials, having one flange parallel to the key-taper, all the

other horizontal flanges being radial. For curves every fifth ring is tapered, giving a 500-foot-radius curve on the centre-line.

The land-lengths of the main tunnel, where cast iron is used, have an upper half similar to that described above, except that the width of ring is 30 inches instead of 24 inches, with seven bolts in the horizontal flanges. A length of tunnel under Dale street, where special strength was required, is of 18-inch rings.

For these land-sections the iron arch formed by the upper half of the tunnel rests on a straight casting, as shown in Figs. 3, Plate 1, which also forms a skewback for the arch of the invert. This latter is generally of concrete construction, but where the Mersey Railway is crossed the invert is of cast iron, built up of segments generally similar to those already described. A completed length forms an inverted segmental arch with an external radius of 33 feet 3 inches and internal radius of 31 feet 1½ inches. The concrete invert is described below.

The amount of cast-iron lining used in the main and branch tunnels and in the shafts totalled about 82,000 tons, and the bolts numbered approximately one million.

Steel and Concrete Lining.

Where cast-iron lining was not considered necessary for the main tunnel, the method of construction was to use rolled-steel joists and concrete filling. This is shown in Figs. 4, Plate 2. The steelwork consists of a series of curved ribs at 2-foot 6-inch centres, each rib being built up of four lengths of 12-inch by 5-inch by 30-lb. rolled-steel joist, butt-jointed, with web cover-plates 10½ inches by 1 inch by 2 feet 3 inches.

The radius of curvature to the inside flange is 22 feet 2 inches, allowing 2 inches of cover for the steelwork to give the standard 22 feet radius for the inner surface of the tunnel. The two upper lengths of joist are completely curved, but the other two lengths at the sides of the tunnel are straight for 3 feet at the lower end. When the joists are in position, this straight length starts at the horizontal diameter of the semicircle and extends vertically downwards to a base-plate which is attached to the lower end of the joist by means of angle-cleats. The weight is distributed over a 1-inch base-plate by means of a second short vertical length of 12-inch by 5-inch by 30-lb. joist, flange to flange with the main rib, which is attached to the base-plate by similar angle-cleats, 6-inch by 4-inch by ⅝-inch.

The base plates rest on a horizontal benching cut in the rock, a bed being formed of 1-to-1 granite chippings and cement. There

was a space of from 3 to 4 inches between the outside of the steel ribs and the rock-face, the ribs being strutted from the rocks during construction by timber wedges and precast concrete blocks.

The whole semicircular arch is completed in 6-to-3-to-1 plain concrete, shuttered on its inner face to a 22-foot radius, so that the tunnel, when the finishing coats are added, has exactly the same appearance as the lengths constructed in cast iron. The thickness of concrete is 1 foot 6 inches from the inner surface to the rock-face. The lengths of tunnel where the above construction is employed are not completely circular in section, but have a concrete invert of the same general form as that used under the cast-iron upper half, in the sections previously described.

The concrete, which is 6-to-3-to-1 as in the upper portion, is laid directly upon the rock-face, and is formed to a 32-foot 2½-inch radius, so centered that the surface, at its lowest point along the vertical axis of the tunnel, is 10 feet below the horizontal axis of the upper semicircle; that is, 8 feet 6 inches below the roadway-surface. The internal height of the tunnel without the roadway is thus 32 feet. Two horizontal benchings were cut in the rock where the foundations for the roadway-supports were formed, but only a skin of concrete 4½ inches thick was laid over the rest of the invert. This type of construction applies to the lengths where the rock is dry or where there is no great water-pressure.

Where a more substantial invert was required the rock was cut to a lower level, and bitumen sheeting was laid on the 4½-inch concrete skin. Above this there is a further layer of 6-to-3-to-1 concrete 13½ inches thick formed to the 32-foot 2½-inch radius, giving a total thickness for the invert of about 1 foot 6 inches. In both cases the invert-concrete merges into the footway- and road-construction at its upper ends.

Excavation.

As has been already mentioned, the site of the tunnel, with the exception of the portions approaching the entrances, lies in the Upper and Middle Bunter Sandstone beds. This sandstone lent itself readily to removal by blasting. The excavation may be divided into three stages, following the sequence of operations: first the pilot-headings, then the upper half of the 46-foot 3-inch external-diameter main tunnel, and lastly its lower portion.

The general method of blasting the headings was as follows:—

The excavation of the upper 7 feet of the face was kept from 8 to 10 feet in advance of the lower portion, thus forming a convenient

working bench (*Figs. 5*). In the centre of this 7-foot drift four horizontal holes, 5 feet in length, were drilled in a converging direction, to create a conical cut. Around this cut further series of holes were drilled, their direction gradually fanning out until the direction of the last series on the perimeter was parallel to that of the tunnel.

The holes, beginning at the central cut, were then charged with gelignite, 1 lb. per hole being used at the cut, diminishing to ¼ lb. per hole at the trimmer series; the charges were fitted with mercury-fulminate detonators and a 6-foot length of black fuse was used. The round, which was limited by the engineers to 12 lbs., was ignited by hand in correct rotation, the fuses burning at a rate of 2 feet per minute. The result of a round gave a progress of from 3 to 4 feet, its success depending on the cut shot.

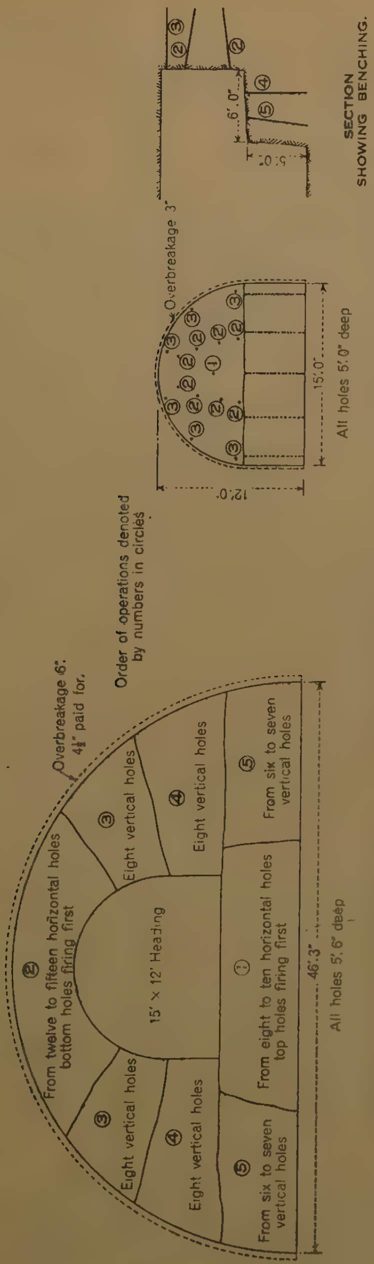
After the removal of the excavated rock from the drift, an equivalent length of the benching was drilled horizontally and vertically, the former direction being required for trimming. The vertical holes were charged with ½ lb. per hole and the horizontal holes with ¼ lb. per hole, and they were fired in that order. The blasting of this portion of the section was greatly helped by the free vertical face of the benching. Progress under this method of blasting averaged 40 feet per week of 110 working-hours, the maximum rate of progress being 60 feet per week. When the restriction on the charges is considered, the progress may be considered good.

In the river-section where two pilot-headings were driven, the lower one was kept in advance, and from it exploratory diamond core-borings were taken to the extremity of the rock; the knowledge thus gained proved of great value as the upper heading approached the "glacial channel." In the land-headings the ground for a distance of 150 feet in advance was explored by three percussive borings.

On the completion of the pilot-headings, the excavation of the upper part of the main tunnel was commenced by means of "break-ups" at points along the line of the tunnel, fourteen faces being the maximum number in the river-section and ten in the land-sections. The excavation in these "break-ups" was carried out by utilizing the pilot-heading as a cut-shot and blasting the rock towards this cavity; the direction of the drilling was then gradually fanned to finish parallel with the tunnel. The weight of charge varied less than in the case of the pilot-headings, and may be taken in general as ½ lb. per hole, diminishing to ¼ lb. per hole at the perimeter.

In the lower portion of the main tunnel the method employed was to blast downwards from the rock-floor at axis-level into the crown of the bottom heading, and the gorge thus created was then worked

Figs. 5.



METHOD OF FIRING CHARGES IN 44-FOOT DIAMETER TUNNEL, AND IN 15-FOOT BY 12-FOOT HEADING.

outwards to the full sections, the drilling being mostly vertical and the weight of charge ½ lb. to ¼ lb. per hole. Owing to the varying nature of the rock and condition of the work, it is difficult to give an exact figure for the weight of gelignite required to excavate 1 cubic yard of rock, but, taking the work as a whole, the pilot-headings showed 1·375 lb. per cubic yard, and the full section 0·80 lb.

Special mention must be made of the contractor's arrangements in the river-section for handling the excavation when a weekly average of 4,000 tons was brought to the surface. When excavating the upper portion, shoots at each working-face were cut in the rock from axis-level of the full section to the crown of the lower heading, and the excavation tipped direct into the wagons and hauled to the shafts. As the faces advanced, fresh shoots were cut and the previous ones used as a means of access for the iron lining which was lifted by a pneumatically-operated winch from the trains in the lower heading. As the work proceeded, and in preparation for the building of the lower portion, a working-road was slung from the finished arch, its level being 2 feet above axis-level, so that, when excavating the lower half, the excavated rock at each face was hoisted to the road-level and conveyed away whilst the iron lining delivered at that level was lowered to the face. By this arrangement each face was independent, and not subjected to delay by the transit of excavation or material belonging to other points of the work.

As the tunnels approached the surface of the ground, tunnelling on the lines hitherto adopted had to be abandoned, and the work was constructed by cut-and-cover and open-excavation methods. At Dale street, however, cut-and-cover work involved considerable interference to traffic, and to the large number of mains below the surface. There was also a risk of subsidence in the foundations of the heavy buildings on both frontages of the street.

After considering these points, the contractor obtained permission to extend the tunnelling operations by using a roof-shield which could be driven right up to the portal of the Old Haymarket entrance. It was erected in a chamber excavated in the solid rock at a distance of 880 feet from the portal, the roof of the chamber being supported by heavy crown-bars which also aided the erection of the shield. The shield was required to work under varying conditions, at first with a complete rock-face excavated by blasting, and later with an increasing face of boulder-clay and made ground. The general outline of its design is shown in Figs. 6, Plate 2.

The frame-members, the semi-annular box-girder containing the rams, and the cutting-edge and skin were built of mild steel. The whole structure was 46 feet 9½ inches in diameter, 12 feet 6 inches in

length, and had a height of 27 feet above the bearing-path level. Propulsion was effected by twenty-four cast-steel hydraulic rams, $8\frac{1}{2}$ inches in diameter and of 2-foot 9-inch stroke, capable of giving a total force of 600 tons at 1,000 lbs. per square inch working pressure.

Provision was made under the working-platforms for supporting the face by six rams, 7 inches in diameter and of 2-foot 9-inch stroke, coupled up to a relief-valve lifting at 1,000 lbs. per square inch at the battery-control. The weight of the shield was 200 tons, and it was borne on steel rollers 4 inches in diameter and 4 feet 9 inches in length at 6-inch centres. For convenience when transferring them ahead on to the concrete path prepared in the headings driven at the tunnel-sides, the rollers were set in frames, six rollers to a frame.

The shield proved quite successful in operation, but on reaching a point where the crown was 12 feet out of the rock, a "run in" occurred. Fortunately, the precaution had been taken of equipping the water-mains in the neighbourhood with screw-down valves, and the inflow of water was speedily checked; tunnelling operations then continued to the portal. Subsequent investigations revealed the fact that during the Parliamentary Wars a deep trench had been dug across what is now Dale street, and the shield had driven into the loose fill and had caused the water-mains to settle and fracture.

Erection of Cast-Iron Lining and Grouting.

The method and general scheme of erection of the iron was to build the upper half first, employing mechanical erectors, and to place the invert-iron in position by means of block, tackle and winch after the completion of the arched top. At the "break-ups" along the pilot-heading, short lengths of arch were erected by stage, block and tackle, just sufficient in length to allow for the installation of an erector-machine which, when completed and advanced, made space for a second machine to work in the opposite direction. The machines consisted of a travelling steel frame equipped with an upper and a lower working-deck. The gearbox and erecting-arm ran on rails between the beams of the decks, the gearbox being capable of cross-traversing and the erecting arm of rotating and telescopic movements, all controlled by compressed-air motors (Figs. 7, Plate 3).

The success of these machines was such that the weight of iron erected reached a peak total of 1,000 tons per week in the river-section alone, twelve plates of 17 cwt. each being the weight of lining to the 24-inch ring-length in the half-section. As a general rule, the nature of the rock permitted the erection of two rings at a time.

Two springer-plates, of differing lengths to allow for the break in the cross joints, were seated upon a steel plate bedded in the rock at axis-level and bolted to the previously-erected iron. Dual erection continued up the haunches to a point where, owing to the weight of overhang, it was advisable to complete the keying-up of the back ring before continuing with the progress of the leading ring, which followed at a short interval. When erecting the invert-iron, the rock at axis-level was undercut from the top iron for a length of just over two rings, the steel plates referred to previously being then removed and the cast-iron plates suspended by their bolts and drawn up into position. The erection was then continued downwards to the final key at the bottom.

During the period of excavation the blasting had been so well controlled that the space behind the cast-iron lining averaged just under 6 inches in the arch and 3½ inches in the invert. As the erection of the lining proceeded, this space was hand-packed with selected pieces of rock, and the open end closed by means of a "sausage," a long fibre bag laid around the back of the iron and expanded by pumping grout into it, the width of the bag allowing it to expand into the crevices of the rock and so make a close seal. These seals were placed at every fifth ring, and enabled the grouting to be performed as a separate operation without interfering with the progress at the face. Cement-grout was then injected behind the lining by working upwards from each side, ordinary bougee-pans being employed, and the pressure being about 80 pounds per square inch.

On the completion of lengths of the full section, further grouting of an intensive nature was carried out by means of a grout-pump with a continuous feed of very thin grout, injected at a pressure of 120 pounds per square inch. The value of this last process may be judged by the fact that, when removing sections of the cast-iron lining for the ventilation and other connections, it was found that the grout had penetrated well into the fissures in the rock.

After the initial grouting had been completed, the machined caulking-grooves, 1½ inch by ¼ inch, between the horizontal and circumferential joints were thoroughly cleaned out, and lead wire of the same diameter as the grooves was caulked into the recesses by pneumatic hammers, in order to make them watertight. The caulking was afterwards subjected to the pressure of 120 pounds per square inch from the intensive grouting, and the failure of any caulking was a most rare occurrence.

The bolts were made watertight by means of bituminous grummets manufactured on a heavy canvas base and placed in position under washers. The washers were of wrought iron, and were dished in section, thus imprisoning the grummets. On tightening the bolts

the collapse of the dishing forced a collar of bitumen into the space between the bolt-shank and the walls of the bolt-hole, any outward flow being impeded by the canvas.

Roadway-Construction.

The roadway is carried on a reinforced-concrete deck throughout the length of the tunnel. This is placed 18 inches below the horizontal diameter of the circular tunnel, and in a similar position in relation to the upper half of the main tunnel where this is constructed with an invert. This position gives the maximum width of roadway which is consistent with the clearance of 16 feet required for high vehicles. There is a 2-inch camber on the roadway-surface. The general form of construction for the reinforced-concrete deck and its supports in the various types of tunnel-section is shown in Figs. 2 and 3, Plate 1, and Fig. 4, Plate 2.

In the under-river length, where the tunnel is circular, the deck is carried on two longitudinal reinforced-concrete walls. These are spaced 22 feet from centre to centre, and equidistant from the tunnel centre-line. For this type of construction the air-supply for ventilation is confined to the two outer spaces, and is led upwards through 12-inch by 4-inch slots placed at 18-inch centres, and formed in the concrete of the deck. Where the tunnel has a concrete invert there is much less height below the deck, and rows of columns 7 feet apart are substituted for the continuous wall. In this case the whole space below the deck is used for the air-supply. Longitudinal reinforcement between the tops of the columns converts the rows in effect into continuous longitudinal supports.

The deck provides for a 36-foot roadway, leaving a space of 4 feet to each side of the tunnel. In this space the upper surface of the deck is constructed to form a curb, a ventilation-slot and a footway having a hollow space below the paving-slab for the accommodation of cables. Handrail-supports are set in the concrete, giving a walking-space of about 2 feet 3 inches at pavement-level. The upper ends of the ventilation-ducts open into the ventilation-channel, which is bell-mouthed to diffuse the air as it enters the traffic-space. One side of the channel is formed in the footway-concrete. The other side is the surface of a specially-shaped pre-cast concrete block. This block also provides a backing for the cast-iron curb which is set in the decking-concrete.

The main reinforced-concrete slab which forms the deck is divided into three sections by the two longitudinal supports. Considered in cross section, the central span is designed as a suspended beam,

8 feet long and 12 inches deep, supported by two cantilevers. The depth of these is 12 inches at the end adjacent to the beam, but is increased to 24 inches over the supports by a curve on the under side of the slab. This 2-foot depth is continued to the side of the tunnel so that the outer spans are beams 2 feet in depth. In construction all the beams and cantilevers are continuous.

The details of the steel reinforcement are shown in Figs. 2 and 3, Plate 1, and Figs. 4, Plate 2. The loading adopted was the Ministry of Transport standard loading for bridges, and particular attention was given to the "punching" effect of heavily-loaded wheels. The placing of the concrete was carried out in complete lengths with as few working-joints as possible. In the circular tunnel a special carriage, mounted on rails, was used to support the shuttering for each length of the central span, and, after striking, it was moved along complete for a new length. In the inverted lengths the columns were erected first, and movable frames were strutted against them. Standard shuttering-frames were then erected over these and on intermediate vertical timbers.

Surfacing of Roadway.

Except for one 500-foot length, where rubber paving was used to reduce vibration over the Mersey Railway, the whole of the main and branch tunnels are surfaced with cast-iron setts. Each sett is composed of a $\frac{3}{8}$-inch flat-topped plate with flanges and ribs on the underside, the whole casting forming an open-bottomed box divided into compartments. The depth of the flanges and ribs is so arranged that most of the weight is carried at the four corners and at the centre. Each sett is $11\frac{3}{4}$ inches square in plan, and has a regular pattern of diamond-shaped studs raised $\frac{5}{16}$ inch above the general surface of the top plate. The depth from the surface of the studs to the base of the flange at the corners is $1\frac{7}{8}$ inches.

The castings were manufactured by a special process devised by the Stanton Ironworks Company, by which it was possible to give the studs specially hard-wearing properties, and to eliminate casting strains. The setts were laid in a bituminous bed which was spread hot over the formed concrete surface. Before laying they were subjected to rigid tests for strength and accuracy. The roadway is divided into four traffic-lanes by lines of rubber blocks, amber in colour, and the edges of the cast-iron setts laid up to these lines had to register with sufficient accuracy to show no visible deviation when viewed along the tunnel. Specially-shaped setts were used at the junction-chambers, and to form the channels and surrounds for the manhole-covers.

On the 500-foot length referred to above, the rubber paving consisted of blocks keyed to a cast-iron base and bedded upon the concrete deck, which was built up to allow for the difference in depth between the cast-iron and the rubber setts. The blocks measured 9 inches by $4\frac{1}{2}$ inches by $1\frac{1}{4}$ inch deep and were black in colour.

Finishing of Tunnel.

The finished appearance of the tunnel is the same whether constructed of cast-iron or of steel and concrete, and the finishing processes are identical in each case. For the cast-iron lengths, however, the segments, as seen from the interior of the tunnel, formed a series of hollow spaces bounded by the flanges. These spaces were all filled up solid with 6-to-3-to-1 concrete. This gave permanent protection for the tunnel-bolts and formed a continuous solid backing for the final waterproofing and finishing processes. The next stage was to apply to the whole of the surface of the tunnel above the roadway a reinforced coat of "Gunite" rendering, consisting of cement and sand sprayed under pressure on to the concrete surface, and having a waterproofing compound incorporated.

The first step in the carrying out of the work was to clean thoroughly the existing surface to which the "Gunite" lining was to be applied. This was generally done by hosing down with a powerful jet of water, although the use of wire brushes and pneumatic scaling-hammers was sometimes found necessary. In addition, any smooth areas of the concrete archway were roughened to assist in providing a bond. On completion of this preliminary work the reinforcement was fixed in position, being kept $\frac{3}{8}$ inch clear of the concrete backing by inserting small distance-pieces. This was to ensure that the rendering would thoroughly incorporate the reinforcement, which was thus placed centrally in it.

For the purpose of smoothing the "Gunite" rendering to a true surface and also to obtain the specified thickness, light wooden screeds were next fixed in position around the perimeter of the arch on top of the reinforcement. They were placed at 8-foot intervals and were fixed to the concrete by means of "Rawlplugs" and screws. The "Gunite" rendering was then applied to its full thickness in one application, each bay (the 8-foot-wide panel enclosed between adjacent screeds) being completed one at a time. When two bays had been finished the intermediate screed was removed and the space previously occupied by the screed filled in.

Light timber gantries, from which the entire perimeter of the arch was easily accessible, were used for scaffolding. Mounted on wheels, their lightness and mobility greatly facilitated the progress of the

work. They were easily convertible for use in either the 44-foo tunnel or in the 26-foot 6-inch tunnels, and later in the junction chambers and ventilation- and exit-shafts. Compressed air fo operating the cement-guns was supplied by the main contractor from their installations on each side of the river, and lighting wa provided by 500-watt portable floodlights mounted on trestles.

As a further precaution to prevent the leakage of water, th "Gunite" finish was then sprayed with "Indasco," a specially stabilized water-emulsion of bitumen. To give a light-coloured permanent, and easily-cleaned finish to the overhead arch of th tunnel, this was completed by a coat of oatmeal-coloured "Astro plax" brand plaster, and was waterproofed with "Marplax" polish

From considerations of appearance and cleanliness, the sides of th tunnel adjoining the footwalks were finished with a black-glass dado The dado is made up of ¼-inch thick sheets of black glass, laid in lead cames and framed with stainless-steel bars. The natura vitreous surface of the glass provides a perfectly durable lining whic is unaffected by moisture or fumes. The dado runs the full lengt of the tunnel to a height of 6 feet 3 inches from the concrete-plint level, and consists of three graduated rows of glass in large sheet supported by means of special rails of non-ferrous metal. These rails are designed with a movable wing or web at the front and wit two contact-cushions at the back, so that, whilst the glass is hel firmly in position, there remains sufficient room for slight movemen due to contraction, expansion, or vibration. This member is als utilized for the vertical joints, which are at approximately 10-foo centres.

The rails are supported by special screws driven into solid lea plugs inserted into the concrete facing and driven home by pressur to a minimum depth of 2 inches; they were left protruding ⅝ inc from the face of the concrete. This was essential to provide an preserve an insulating space between the concrete and the back o the glass both in order to allow variations of alignment to be over come, and also to give accommodation for lighting cables and con densation tubes, as well as to prohibit any movement of the mai structure being transferred to the surface of the glass. The screw securing the rails to the plugs are of stainless steel with a specially designed thread, and are of such a length that the whole of th thread is embedded in the plug.

These supporting members, both vertical and horizontal, ar ultimately faced by special stainless-steel members which add to th security and support of the glass, and are of a profile which prevent the lodgment of dust and facilitates cleaning. Special treatment ha been given to the doorways, splays and junctions, all of whic

conform to the general alignment and design. No further interior decoration for the tunnel was considered necessary, and as completed, it presents a perfectly plain and smooth finish, unbroken except for the fire-stations at intervals along the footways, the various signs at the junctions, emergency entrances and the two rows of sunk-lighting fittings which are flush with the plaster-surface. The handrails along the edges of the footways are painted red and cream.

Branch Tunnels.

These tunnels have a semicircular upper half of 13-foot 3-inch internal radius, and vertical sides, the width of 26 feet 6 inches between these allowing for a 19-foot roadway and two footpaths each 2 feet 3 inches wide (Figs. 8, Plate 3). Where the tunnels are constructed in cast-iron the depth of flange is 9 inches, giving an external radius of 14 feet. The vertical sides are formed of flat castings similar to the segments. The lowest casting on each side, which takes a bearing on the rock with the usual bed, has a depth of flange which increases towards the base, where it is 1 foot 3 inches. Above the line of these castings the plates break joint as in the main tunnel, but an ordinary hollow key is used instead of a solid block. The concrete filling to the castings is 5-to-3-to-1, as in the main tunnel.

Where the steel and concrete construction is used, the general shape is the same as for the cast-iron lengths, and the general construction is similar to the main tunnel, except that the joists are 9 inches by 4 inches by 21 lb., and that these are in three lengths instead of four. The radius to the inner face of the joist is 13 feet 5 inches, and the thickness of concrete is 1 foot $3\frac{1}{2}$ inches. The concrete invert is formed to a 16-foot $1\frac{1}{2}$-inch radius on its upper face, the centre being 2 feet $7\frac{1}{2}$ inches above the horizontal diameter of the upper semicircle. This makes the lowest point in the invert about 14 feet 5 inches below the horizontal diameter, or 7 feet 2 inches below the roadway-surface. The internal height of the tunnel without the roadway is thus 27 feet 8 inches.

Entrance-Plazas.

The plazas at each entrance called for quite a lengthy study, as not only had they to be large enough to accommodate the traffic for years to come, but they had to be so designed that vehicles could stop at the toll-booths without causing delay and congestion. Experiments were carried out with temporary toll-booths placed in different positions, and their number and position arrived at by this means. It was found that toll-booths placed radially to the tunnel-

entrance were capable of handling the traffic much more efficiently than if they were placed in series. Four toll-booths were provided at each of the main entrances, but the branch tunnels have only two toll-booths at each entrance.

Ventilation.

The ventilation of the tunnel was a matter that received very careful consideration from the beginning of the scheme. The late Dr. J. S. Haldane was called in to advise before the Bill came before Parliament, and the evidence that he gave to the Parliamentary Committees was sufficient to show that the problem could be successfully solved. At that time, namely 1925, no subaqueous tunnel of similar capacity was in actual operation and no previous experience was available, but the Holland tunnel in New York was under construction, and a number of experiments had been carried out by the authorities in charge of it. By the autumn of 1929 that tunnel had been in use for 2 years, and, in order to have first-hand knowledge of the method employed there, the late Mr. B. H. M. Hewett, M. Inst. C.E., and Mr. J. E. Lister, Assoc. M. Inst. C.E., went over to investigate it and to report thereon. Their report was duly considered, and it was decided that the system employed was a satisfactory one and should be used at the Mersey tunnel, subject, if necessary, to certain modifications.

As the Holland tunnels are twin, each providing for two lines of traffic, the latter is one-way and itself creates a longitudinal movement of air which, to a certain extent, makes the tunnels self-ventilating. In the Mersey tunnel, however, the main tunnel carries four lines of traffic, moving in both directions, and the air is therefore constantly being churned up. In the branch tunnels, the conditions are similar.

It was evident that, before the type of ventilation employed in the Holland tunnel was adopted for the Mersey tunnel, full-scale experiments ought to be carried out. It was not possible to carry out this investigation until the end of 1930, by which time a section of the tunnel 1,000 feet in length under the Birkenhead side of the river had been completed. It was isolated from the remainder of the work by means of a brick bulkhead at each end and a removable ceiling fitted with adjustable openings in it.

The fresh air in the Holland tunnel is introduced by fans into a longitudinal duct placed under the roadway. The air escapes into the body of the tunnel by means of a longitudinal slot in each curb, this slot being connected to the main duct by means of numerous cross-connections. The width of the slot is

adjustable to ensure that equal quantities of air escape into the tunnel for each foot of its length. The vitiated air, being warmed by gases emitted by motor-cars using the tunnel, tends to rise to the ceiling, and is drawn into a longitudinal duct constructed therein by means of exhaust-fans at the ventilating-stations, where it is discharged into the open air.

For the Mersey tunnel, however, it was considered that, in view of its dimensions being so much larger than those of the Holland tunnels—namely, 44 feet internal diameter and 23 feet 6 inches from roadway to soffit, as against 27 feet 2 inches internal diameter and about 20 feet from roadway to soffit—the system so successfully adopted at New York might not prove equally successful at Liverpool, and the experiments decided upon were directed towards three different systems, namely:

(1) The upward transverse system (as in the Holland tunnels).
(2) The downward transverse system.
(3) The upward semi-transverse system.

The first system has already been described. In the second, the fresh air was introduced into the upper duct, and the vitiated air was extracted by means of the duct under the roadway. In the third system, the fresh air was introduced from under the roadway, as in the first system, but instead of extracting the vitiated air by means of the top duct, this top duct was omitted and the whole cross-section of the tunnel from roadway-level upwards was used as a duct, the air being exhausted as before.

Temporary blowing- and exhaust-fans were installed, each having a capacity of 300,000 cubic feet of air per minute. Quantities of petrol up to 20 gallons at a time were spilt over the roadway and ignited, and bales of damp hay and straw were set on fire to produce dense clouds of smoke. Smoke candles were employed to enable the air-currents to be observed in detail, and a movable steam-boiler, emitting heavy clouds of smoke, was also employed. The flow of air in the ducts and in the tunnel was accurately measured by means of suitable instruments, and an exhaustive series of experiments was carried out. It was finally decided to adopt the upward semi-transverse system. The experiments showed that the top duct could quite well be omitted, thus saving its cost and greatly reducing the amount of power required for the removal of the vitiated air. The downward transverse system was a failure, not only because it had to act against the natural tendency of the heated air to rise, but because it brought down to eye-level the smoke that would otherwise have remained at ceiling-level.

The amount of fresh air finally decided upon was based upon the assumption that 1·5 cubic foot of carbon monoxide is emitted

by a motor-car per minute; this is distinctly high. With motor-cars proceeding through the tunnel at intervals of 75 feet and at a speed of 20 miles per hour, all tracks being occupied, this gives 200 cubic feet of air per minute per foot run of main tunnel, and 120 cubic feet of air per minute per foot run of branch tunnel. The maximum dilution has been taken to be 2·5 parts of carbon monoxide per 10,000 parts of air at times of peak traffic; under ordinary conditions it will be well below this figure. At the present time it does not exceed one part in 10,000. At these dilutions there is no danger at all to persons using the tunnel. At the higher rate, the traffic police, unless already acclimatized, might suffer from slight headaches if on duty in the tunnel for long.

Six ventilation-stations have been provided, three in Liverpool and three in Birkenhead. Those in Liverpool are situated at George's Dock, North John street and New Quay, whilst those in Birkenhead are at Woodside, Sidney street, and Taylor street. The sites chosen for the ventilation-stations were dictated by the exigencies of the ground; in consequence, several of the stations are on sites which do not permit of the most favourable arrangement of ducts between the fans and the tunnel. In addition, the restricted layout of certain sites, particularly North John street, made it difficult to arrange the fans within the building in such a manner as to permit of their efficient operation. In consequence of the large number of bends of fairly sharp radius necessary in the approach-ducts, great care had to be taken in forming these bends and, where necessary, in introducing deflectors and guide-vanes for avoiding violent eddying and loss of power. This, however, was done with such effect that the actual resistance of the approach-ducts proved to be less than that estimated in practically all cases.

After the experiments in 1930 in the completed section of tunnel at Sidney street had determined the method of ventilating the roadway, it was decided to carry out further experiments in order to find a suitable type of fan for the purposes in view. Most of the fans required for the ventilation of the tunnel were of very large size, closely comparable with those found in coal-mining practice. It was, therefore, decided to examine the various types of fans used in collieries in Great Britain and elsewhere. At the same time it was realized that considerable savings in the size of buildings and layout of the approach-ducts could be achieved if it were possible to make use of the propeller or axial-flow type of fan. Investigations showed that one such design of fan, namely the Walker-Steart, was in commercial use, and it was finally decided to carry out comparative efficiency-trials on a "Walker-Steart" propeller-fan and on a

"Sturtevant" centrifugal fan, as representing the more usual type of large fan.

Great care was taken with these experiments, and what is probably the largest fan-testing gallery in the world was set up on a suitable site at Rendel street. Both fans, designed to pass 300,000 cubic feet of air per minute against a water-gauge of 3 inches, were connected up by means of a breeches-duct to a straight gallery 150 feet long and 12 feet square. The open end of the gallery could be closed by sliding doors so as to impose a resistance which could be adjusted to any value against the fans. An instrument-station was set up one-third of the length of the duct from the open end, and great care was taken, by the use of calibrated anemometers, manometers, and watt-meters, to obtain the true efficiencies under working-conditions.

These experiments showed that the propeller-fan in its then stage of development was not equal to the centrifugal fan in efficiency, and moreover gave rise to a considerable amount of noise, both from the rotation of the fan and also from the air-stream discharged through the fan. It was, therefore, decided to adopt the centrifugal fan at all stations. An opportunity was also taken on the experimental set at Rendel street to test the hydraulic coupling on one of the fans. The results obtained were such as to justify the use of these couplings on the equipment of the tunnel.

It was realized at an early stage that the ventilation-buildings, particularly at North John street and at George's Dock, would be on sites in close proximity to important public and commercial buildings, and that any undue noise from the fans or equipment might be an intolerable nuisance. Careful noise-tests were therefore carried out, both to ascertain what was the normal level of noise in the streets, and also what was the level of the noise produced by the fans. It is of interest to note that during a busy morning, a general noise-level in the streets of about 80 decibels was recorded and that a rather higher figure was found for the centrifugal fan. It was, therefore, essential to take such steps in the construction of the buildings, in the mounting of the fans and motors, and in guiding the air-stream well above building-roofs as would prevent a nuisance. The care taken in this respect has justified itself, and no trouble has been experienced.

Before a reasonable forecast of the conditions of pressure- and flow-distribution throughout the air-ducts and traffic-space of the tunnel could be made, it was necessary to examine the problem both from a theoretical aspect and also in the light of all available experimental or published information which was applicable to the problem. As the semi-transverse system of ventilation had been

decided upon, little difficulty was experienced in estimating the pressure required at the exhaust-fans to maintain the required rate of flow for the vitiated air leaving the roadway. The total resistance against which the fans had to operate was due to the sum of the resistances of the short ceiling under the exhaust-shafts, of the ducts leading to the exhaust-fans themselves and of the dampers admitting air to the fan-rooms. The resistance of the large traffic-space is negligible and the pressure in the traffic-space nearly atmospheric throughout, with little or no air normally entering or leaving the portals.

The blowing system comprises the fans, blowing ducts leading to the tunnel, the air-ducts below the road-deck, and the slots from the latter to the curbs. The principal problem was to calculate the pressure which had to be applied to the inlet-end of the tunnel air-ducts to force in the quantity of air required per minute for that section as far as the bulkhead, whilst permitting a continuous and uniform leak of air into the roadway.

The magnitude of the drop in pressure due to friction-loss in a duct of uniform cross section may be stated as :—

$$h = \frac{flv^2}{2gm} \text{ feet of air} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f denotes a friction-coefficient,

l ,, the length of the duct in feet,

v ,, the velocity of flow in feet per second,

m ,, the hydraulic mean radius in feet.

Examination of the rather scanty information available indicates that the value of the friction-coefficient is not constant. Mr. O. Singstad gives for the Holland tunnel the value

$$f = a + \frac{b}{m^2v^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $a = 0{\cdot}0035$ and $b = 0{\cdot}01433$.

The Mount Victoria Report (New Zealand) quotes a formula which, when reduced to similar terms, gives the values for a and b as 0·00342 and 0·028, respectively. In the Mersey tunnel the inlet-velocity to any section is never less than 15 feet per second with the full quantity of air passing. The portion of the coefficient represented by b may, therefore, be neglected without any appreciable error.

Fundamental consideration of the change of total pressure along a duct with a uniform air-leak yields the following expression for the total pressure-drop between any point in the duct and the bulk-head :—

$$\frac{p_x - p_0}{w} + \frac{v_1{}^2x^2}{2gl^2} = \frac{v_1{}^2}{2gm}\left(\frac{ax^3}{3l^2} + \frac{bx}{m^2v_1{}^2}\right) \quad . \quad . \quad . \quad (3)$$

where p_x denotes the pressure at the selected point,
p_0 ,, pressure at the bulkhead,
v_1 ,, inlet velocity,
x ,, distance from the bulkhead to the selected point,
l ,, distance from the bulkhead to the inlet.

In the Mersey tunnel b may be neglected and the expression simplified to :—

Total pressure at the selected point

$$= \frac{v_1^2}{2gm}\left(\frac{a_1x^3}{3l^2}\right) + \frac{p_0}{w} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

This expression may be compared with that given by Mr. Singstad for the new Holland tunnel for the static pressure required :—

$$\frac{p_x}{w} = \frac{v_1^2}{2gm}\left(\frac{ax^3}{3l^2} + \frac{bx}{m^2v_1^2} - \frac{m(1-k)x^2}{2l^2}\right) + \frac{p_0}{w} \quad . \quad . \quad (5)$$

Restating equation (3) for static pressure,

$$\frac{p_x}{w} = \frac{v_1^2}{2gm}\left(\frac{ax^3}{3l^2} + \frac{bx}{m^2v_1^2}\right) - \frac{v_1^2x^2}{2gl^2} + \frac{p_0}{w} \quad . \quad . \quad . \quad (6)$$

or
$$\frac{p_x}{w} = \frac{v_1^2}{2gm}\left(\frac{ax^3}{3l^2} + \frac{bx}{m^2v_1^2} - \frac{mx^2}{l^2}\right) + \frac{p_0}{w} \quad . \quad . \quad . \quad (7)$$

Comparing equations (5) and (7) it will be seen that the third portion within the bracket, $\frac{mx^2}{l^2}$, becomes in the American formula $\frac{m}{2}(1-k)\frac{x^2}{l^2}$. Mr. Singstad gives a value for k as 0·615, reducing the value of the expression to 0·1925 mx^2/l^2. This has the effect of materially increasing the values of static pressure obtained from equation (5) as compared with equation (7) when the Singstad values of a and b are used in both expressions.

During the tests which were made on the experimental length of the tunnel in 1930, a series of values were obtained for the pressure-drop along the blowing ducts in the 44-foot inverted tunnel. Using equation (4) a value was obtained for the coefficient in equation (2) which would satisfy these experimental values. It was not found possible to obtain suitable values for a and b in the Singstad expression, and this latter formula did not give a sufficiently close approximation to the actual form of pressure-curve obtained on the Mersey tunnel. Equation (4) was, therefore, adhered to throughout.

Since the entrances to the riser-slots are sharp-edged, it was assumed that the usual discharge-formula holds good :—

$$\frac{p_1 - p_2}{w} = \frac{v^2}{2gk^2c^2}$$

where $\frac{p_1}{w}$ denotes the static pressure-head in feet of air in the duct.

$\frac{p_2}{w}$,, ,, ,, at the *vena contracta*.

v ,, velocity at the *vena contracta* in the riser-slot.

k ,, coefficient of contraction $= 0{\cdot}63$.

c ,, ,, velocity $= 0{\cdot}97$.

Examination of the static-pressure curve in any duct shows that it reaches a minimum value at some point along the duct-length, beyond which recovery of pressure takes place and the static pressure rises (*Figs. 9*). At this point of minimum pressure, the slots are left full open and the opening of the slots on either side whether toward the bulkhead or towards the inlet is restricted by an amount necessary to permit of the discharge of equal quantities from each slot. To enable this to be done rapidly a simple expression was deduced as follows :—

$$r = \frac{1{\cdot}589v}{\sqrt{(4105h + 0{\cdot}3466v^2)} + v},$$

where r denotes the ratio $\frac{\text{(full opening of slot)}}{\text{(required restricted opening)}}$.

v ,, velocity of discharge taken on the area of full opening in feet per second.

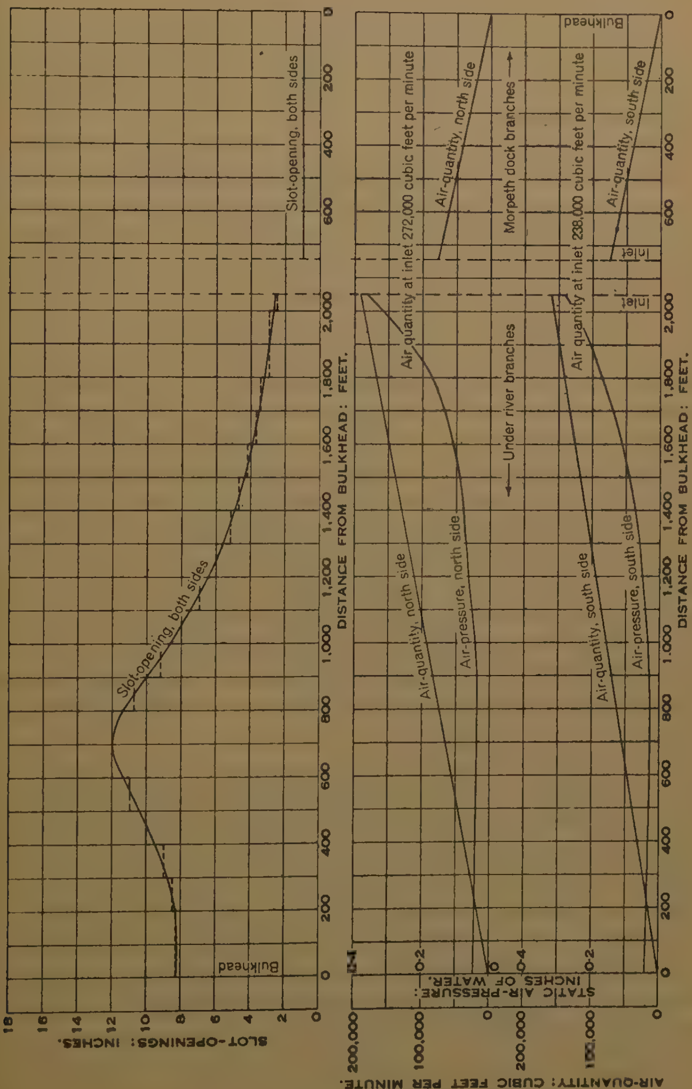
h ,, difference between the static pressure at the slot requiring regulation and the minimum static pressure in inches of water.

This expression was used to calculate the amount of regulation required by all the 20,000 slots throughout the tunnel, and gave satisfactory results.

It was considered unnecessary and impracticable to set every slot to a different value, and compromise values shown by the stepped dotted lines were taken, giving constant openings for all slots in each 100-foot length. This method proved quite successful and, except for some re-adjustment in the set at the first section (New Quay), the air-distribution throughout, as obtained from the initial slot-setting, proved satisfactory. No further adjustment has been made since the opening of the tunnel.

It was important to be able to measure accurately the total quantity of air entering each air-duct. A calibrated measuring-

Figs. 9.



Air-Supply Curves for Woodside Ventilation-Building.

station was therefore established in each approach-duct. In no instance was it possible to find a straight portion of duct of sufficient

length to give really steady conditions of flow, and in all cases turbulence, eddying, and rotation of flow were encountered. Tests were carried out to ascertain whether the vane-anemometer or the Pitot tube gave the more reliable results, using in all cases instruments calibrated by the National Physical Laboratory, and it was found that the new N.P.L. type of Pitot tube was the least liable to error under the conditions existing. Various types of vane-anemometer gave widely different results.

In each approach-duct a measuring-station was wired off into squares to permit of the instrument being traversed over the full section. A so-called standard Pitot tube was fixed to a bracket on the side of the duct at each station and a traverse was carried out, taking simultaneous readings of both traversing and standard Pitot tube. This was repeated at different velocities, and a correction factor was obtained to enable the standard Pitot tube to be corrected to give the true average velocity, correction being also made for skin-effect. In subsequent tests it was therefore only necessary to observe the readings of the standard Pitot tube.

The head registered by the Pitot tubes was read on carefully-calibrated Kent curved-tube manometers filled with paraffin. In addition to these main measuring-stations, wired measuring-stations were set up in the tunnel air-ducts at distances of 100 feet apart throughout. In checking the air-distribution in any given section, conditions of steady flow were set up and maintained, and readings taken at each station throughout the duct from inlet to bulkhead; for these readings the anemometer was usually found more convenient than the Pitot tube. The readings so obtained were plotted, and the distribution obtained examined and corrected, if necessary, by further adjustment of the slots (*Figs. 9*).

After the tunnel was put into operation in July, 1934, it was decided to test the efficiency and performance of selected fans in order to see how far the duty required was being obtained and how nearly the guaranteed efficiencies were being reached. The method laid down in the recently-published "Standard Specification for the Testing of Mine Fans," issued by the Institution of Mining Engineers, was adopted. The quantity of air per minute passed by each fan was measured at the calibrated stations previously described. The pressure generated by the fan was measured by "Kent" curved-tube manometers connected by rubber piping to Pitot-tube heads placed on either side of the fan.

The electrical input to the motors was read by calibrated wattmeters, the efficiency of the motors and gearing having previously been obtained from tests carried out by the makers, Messrs. Metropolitan-Vickers Electrical Company, Ltd. In these tests duplicate

sets of motor and gearing were coupled back to back, the first set acting as the driver and the second set operating as a generator. After one test the two sets were reversed and the mean reading obtained at different loads and speeds.

It was estimated that the fan-efficiencies so obtained were accurate to about 5 per cent., the biggest source of error being the difficulty of reading air-velocities at the measuring-stations. The result of these trials was satisfactory and practically all the fans tested complied closely with the guarantees. In two cases an efficiency considerably higher than the guarantee was obtained, and in one case only was the efficiency substantially lower than that guaranteed. This latter case was largely due to the unavoidably bad arrangements of the fans in a ventilation-building of an awkward shape.

Fans, Motors, and Driving-Gear.

A total of thirty fans and thirty motors has been provided. Table I (pp. 502 and 503) gives their particulars and shows where they have been installed.

It will be seen that both the blowing and the exhausting sets are in duplicate at each station, thus giving 100 per cent. spare plant. This, although somewhat expensive in itself, greatly simplifies the control and cabling arrangements.

Sixteen of the fans were provided by Messrs. Walker Brothers (Wigan), Ltd., and are of their "Indestructible" type. Their impellers consist essentially of two cast-iron bosses, with two mild-steel disks between them. Between these disks are secured mild-steel plates which project outwards and form the arms supporting the fan-blades. The bosses and disks are held together by turned bolts and nuts and are secured to the shaft by keys, whilst the steel blades are attached to the arms by steel angles. The shafts are of mild steel, the largest being 18 inches in diameter. Each shaft is carried in two pedestals, with ring-lubricated sleeve-bearings which are mounted on girders placed in the fan-inlets. The impellers are 21 feet, 25 feet, and 28 feet in diameter, and run at varying speeds up to 80 revolutions per minute.

The remainder of the fans, fourteen in number, were supplied by the Sturtevant Engineering Company, Ltd., and are of their "GV" type. The impellers are built up on circular steel disks, which are carried by two cast-steel half-hubs, mounted on forged-steel shafts, the latter having a maximum diameter of 16 inches. All the shafts are carried in spherically-seated roller-bearings, those at the driving-end consisting of two Hoffmann roller-bearings, and those at the outer end consisting of one roller journal-bearing and one ball location-

Station.	Exhauster Units.
George's Dock.	One { 400 HP., 735 r.p.m.; 128 HP., 485 r.p.m. } One { 400 HP., 735 r.p.m.; 59·5 HP., 365 r.p.m. } Both the above motors drive 28-ft. diameter fans, capacity 599,000 cubic feet of air per minute, through 38-in. nominal diameter hydraulic couplings and double-reduction gears.
Woodside.	One { 430 HP., 735 r.p.m.; 139 HP., 485 r.p.m. } One { 430 HP., 735 r.p.m.; 63·5 HP., 365 r.p.m. } Both the above motors drive 28-ft. diameter fans, capacity 641,000 cubic feet of air per minute, through 38-in. nominal diameter hydraulic couplings and double-reduction gears.
Sidney street.	One { 310 HP., 735 r.p.m.; 95 HP., 485 r.p.m. } One { 310 HP., 735 r.p.m.; 41 HP., 365 r.p.m. } Both the above motors drive 14-ft. diameter fans, capacity 577,000 cubic feet of air per minute, through 35-in. nominal diameter hydraulic couplings and single-reduction gears.
North John street.	One { 230 HP., 735 r.p.m.; 75 HP., 485 r.p.m. } One { 230 HP., 735 r.p.m.; 35 HP., 365 r.p.m. } Both the above motors drive 28-ft. diameter fans, capacity 522,000 cubic feet of air per minute, through 32-in. nominal diameter hydraulic couplings and double-reduction gears.
New Quay.	One { 40 HP., 730 r.p.m.; 12·5 HP., 485 r.p.m. } One { 40 HP., 720 r.p.m.; 6 HP., 365 r.p.m. } Both the above motors drive 7-ft. 6-in. diameter fans, capacity 92,000 cubic feet of air per minute, through 23-in. nominal diameter hydraulic couplings and single-reduction gears.
Taylor street.	One { 30 HP., 730 r.p.m.; 9 HP., 485 r.p.m. } One { 30 HP., 720 r.p.m.; 4 HP., 365 r.p.m. } Both the above motors drive 9-ft. diameter fans, capacity 137,000 cubic feet of air per minute, through 23-in. nominal diameter hydraulic couplings and bevel single-reduction gears.

Blower Units.

One { 350 HP., 735 r.p.m.
113 HP., 485 r.p.m.

One { 350 HP., 735 r.p.m.
52·5 HP., 365 r.p.m.

Both the above motors drive 25-ft. diameter fans, capacity 496,000 cubic feet of air per minute, through 35-in. nominal diameter hydraulic couplings and double-reduction gears.

Two { 175 HP., 735 r.p.m.
57·5 HP., 485 r.p.m.

Two { 175 HP., 735 r.p.m.
27·5 HP., 365 r.p.m.

Each of the above motors drives a 21-ft. diameter fan, capacity 280,000 cubic feet of air per minute, through 32-in. nominal diameter hydraulic coupling and a double-reduction gear.

One { 120 HP., 730 r.p.m.
36 HP., 485 r.p.m.

One { 120 HP., 730 r.p.m.
16 HP., 365 r.p.m.

One { 35 HP., 730 r.p.m.
11 HP., 485 r.p.m.

One { 35 HP., 720 r.p.m.
5·5 HP., 365 r.p.m.

The two 120-HP. motors drive 13-ft. 6-in. diameter fans, capacity 350,000 cubic feet of air per minute, through 29-in. nominal diameter hydraulic couplings, and the two 35-HP. motors drive 10-ft. 3-in. diameter fans, capacity 166,000 cubic feet of air per minute, through 23-in. nominal diameter hydraulic couplings, in all four instances through single-reduction gears.

One { 115 HP., 730 r.p.m.
38 HP., 485 r.p.m.

One { 115 HP., 730 r.p.m.
18·5 HP., 365 r.p.m.

One { 65 HP., 730 r.p.m.
23 HP., 485 r.p.m.

One { 65 HP., 725 r.p.m.
11·5 HP., 365 r.p.m.

The two 115-HP. motors drive 23-ft. diameter fans, capacity 312,000 cubic feet of air per minute, through 29-in. nominal diameter hydraulic couplings, and the two 65-HP. motors drive 23-ft. diameter fans, capacity 234,000 cubic feet of air per minute, through 26-in. nominal diameter hydraulic couplings, in all four instances through double-reduction gears.

One { 55 HP., 730 r.p.m.
17 HP., 485 r.p.m.

One { 55 HP., 725 r.p.m.
8 HP., 365 r.p.m.

Both the above motors drive 9-ft. diameter fans, capacity 145,000 cubic feet of air per minute, through 26-in. nominal diameter hydraulic couplings and single-reduction gears.

One { 40 HP., 730 r.p.m.
12·5 HP., 485 r.p.m.

One { 40 HP., 720 r.p.m.
6 HP., 365 r.p.m.

Both the above motors drive 10-ft. 3-in. diameter fans, capacity 173,000 cubic feet of air per minute, through 23-in. nominal diameter hydraulic couplings and bevel single-reduction gears.

bearing. The centre plates are in one piece, turned all over. The blades, which have a considerable backward curvature, were pressed in dies to give a uniform shape and thickness, and are riveted both to the centre plates and to the outer shrouds, the latter being coned to give as nearly a streamline flow as possible to the air passing through the impeller. The impellers are 14 feet, 13 feet 6 inches, 10 feet 3 inches, 9 feet, and 7 feet 6 inches in diameter.

The outlets of all the Sturtevant blower-fans are provided with balanced dampers supported on ball-bearings and built up on a framework of steel channels. Similar dampers are also provided for the exhauster-fans at the points where the exhaust-shafts from the tunnel enter the fan-chambers, each fan being isolated in a separate chamber to prevent any short-circuiting of the air drawn from the tunnel. The dampers are normally operated through worm and spur gearing by a small motor, but provision is also made for operation of the dampers by hand. A system of limit-switches is provided to prevent the fans being started except when the damper-doors are in the correct position. For both types of fans the casings are of reinforced concrete, with a view to the reduction of noise and vibration.

The motors are of the squirrel-cage pattern, and are supplied with alternating current at 400 volts. The drive from each motor is taken through an hydraulic coupling and a reduction-gear to the fan, connection to the fan being made by a cardan-shaft and two Bibby flexible couplings. Each motor has two windings on the stator, giving a high-speed rating at maximum output and a low-speed rating at a reduced output. Also, in each pair of ventilating units, the low-speed designed ratings are so arranged that from every pair of units three alternative high-efficiency ratings are available. Still further variation of output is obtained by varying the speed of the fan by means of the hydraulic coupling.

The driving-units have been designed with particular regard to quiet running. The ventilating stations are controlled from a central control-room, and, in order that each station may be provided with the minimum supervision, thermostats have been fitted to all the bearings of the motors, reduction-gears, and fans, so that, in the event of any one bearing becoming unduly overheated, the electrical control-gear will shut down the set concerned. The motors running in the exhaust-chambers are separately pipe-ventilated through a duct from the adjoining fresh-air shaft.

The hydraulic couplings enable the motors and gears to pick up their load smoothly and without shock, a feature of importance as the fans range in weight from 3·35 to 23·75 tons. They also make it possible for the motors to be started without load. In construction,

each coupling consists of an impeller and inner and outer casings, all fixed to the driving-shaft of the motor, together with a runner which is fixed to the high-speed driven shaft of the reduction-gear; the stationary parts consist of a manifold, a scoop-tube, and a scoop-tube housing. There is no mechanical connection between the impeller and the runner, power being transmitted by the kinetic energy of oil discharged by the impeller directly against the vanes of the runner.

When full of oil, the slip is of the order of $3\frac{1}{2}$ per cent., the driven shaft then revolving at its maximum speed. By running only partly full of oil, the speed of the driven shaft may be decreased as desired, while by allowing the coupling to empty, the driven shaft may be disconnected from the driving motor. Hence the latter can be started up light, and starting and accelerating torque applied by admitting oil to the coupling.

For speed-regulation, a small quantity of oil is continuously circulated from a gravity supply tank through a tubular control-weir into the centre of the working-chamber of the coupling, and back through ports in the inner casing and the scoop-tube to the elevated gravity-tank. Speed-regulation is effected by lowering or raising, by means of a small motor, the tubular weir in the gravity-tank, thus varying the rate of flow of the oil into the coupling and regulating the speed as desired.

The reduction-gears at George's Dock, Woodside and North John street are of the double-reduction type, the first reduction being by bevel-gears with spiral teeth and the second reduction by spur-gears with single helical teeth. The reduction-gears at Sidney street and New Quay are of the single-reduction type with spur-gears having single helical teeth. The reduction-gears at Taylor street are of the single-reduction type with bevel gears having spiral teeth. All the reduction-gears are mounted in cast-iron cases, with oil-wells into which the gears dip for splash-lubrication. All the bearings are of the roller type, with protecting thermostats, and for every shaft a ball location-bearing is provided. At the end of the intermediate shafts in the double-reduction gears, and at the end of the low-speed shaft in the single-reduction gears, a small gear-driven, permanent-magnet type generator is fitted and is connected to a voltmeter-type instrument calibrated as a speed-indicator.

Reference has been made already to the cardan-shaft and two Bibby flexible couplings connecting the low-speed gear and the fan. The shaft is made sufficiently long to leave plenty of space between the reduction-gear and the fan inlet-plate, in case it should be desired at any time to withdraw the impeller. The two Bibby flexible couplings, fitted one at each end of the cardan-shaft, by their

construction and design allow and compensate for slight variations from accurate alignment. A valuable characteristic of the Bibby couplings is their inherent tendency to damp out vibrations, such as in the present case might arise from the definite number of impulses, corresponding to the number of vanes, given to the air during every revolution of the fan, or from driving unit-noises which might be transmitted from the gears to the building.

To eliminate further the transmission of vibration and noise, mats and packing of special insulating material have been placed under and around the concrete beds of the motors and gears. Similar treatment has also been given to the foundations of the contactor-cubicles and transformers and also to the supports for the cables for a distance of 30 feet from the main driving-motors.

The 3-phase 50-cycle electric supply is brought at 6,000 volts to the George's Dock and North John street stations from the Liverpool Corporation system, and at 6,600 volts to the Woodside and Sidney street stations from the Birkenhead Corporation system, all feeders being in duplicate. The New Quay and Taylor street stations are operated at 400 volts, taking their supply from transformers situated in the North John street and Sidney street stations respectively. All the 6,000-volt and 6,600-volt circuits are controlled by metal-clad switch-gear. All the circuit-breakers directly controlling the fans and tunnel-services in all the stations can be operated either by hand or electrically from the central control-room.

In the high-tension stations, 3-phase transformers are provided which convert the 6,000/6,600 volt high-tension supply to low-tension current at 400 volts for the fan-motors and the control- and lighting-circuits. They are all of the oil-insulated self-cooled type.

The actual starting of the fan motors is done by means of electromagnetic, clapper-type contactor control-gear with push-button control. These contactors are housed in special cubicles which also contain all the necessary interlocking protective gear and other control-apparatus necessary for operating the fans.

Ventilation-Buildings.

The size of the fans required involved the construction of large buildings to house them, and it was by no means easy to secure suitable sites, especially in Liverpool where the tunnel runs under the principal business-quarter. The site that had eventually to be selected at New Quay is situated too near the open portal to be altogether satisfactory.

The following Table gives the internal volumes of the buildings and the heights of the exhaust-shafts :—

	Volume: cubic feet.	Height of exhaust-shaft: feet.
New Quay, Liverpool	321,710	93
North John street, Liverpool	1,130,890	170
George's Dock, Liverpool	1,592,955	200
Woodside, Birkenhead.	887,700	210
Sidney street, Birkenhead	1,190,017	122
Taylor street, Birkenhead	324,470	102

The height of the exhaust-shaft depended usually upon the height of the neighbouring buildings, as it was desirable that the air discharged should be kept above them. This does not apply to Woodside, where the height is due to the constricted site available. The buildings consist of a steel framework, the external walls being of brickwork, except at George's Dock, where the whole of the outside is faced with Portland stone to harmonize with the Dock Office, the Cunard Building and the Liver Building, all of which adjoin it. At North John street, the front towards that street is faced with Portland stone. The external walls were in most cases built in two thicknesses, with a cavity between to reduce the transmission of noise and vibration; external windows have been avoided for the same reason.

The design of the buildings, both internally and externally, was difficult and unprecedented, and the Architect is to be congratulated on the way he has overcome the many problems set him, and on the imposing buildings achieved. Figs. 10, Plate 3 show the ventilation building at North John street, which may be taken as typical of one of the main stations. The framework is of structural steel, whilst the floors and roof are of reinforced concrete. About 2,000 tons of steelwork was used in this building, about 6,000 tons of steelwork being incorporated in the six buildings.

Control-Room.

A control-room has been installed in the George's Dock ventilating building, from which not only the fans in each station can be started up or stopped, but from which the subsidiary services and the traffic can be controlled. The installation consists of two control-boards, a recorder-board and a telephone- and fire-alarm board.

The two control-boards are situated to the right and left of the operator's desk, each being arranged in three sections, representing the ventilating-stations on the Liverpool and Birkenhead sides of the river respectively. In front of the desk, at the far end of the control-panels, is placed the recorder-board which contains eleven

panels arranged in semicircular form, and behind the operator's desk is situated the telephone and fire-alarm board.

In the control-boards, each section consists of a central panel flanked on both sides by either two or three separate panels, according to the number of fan-units in the station. Each of the central panels for the four 6,000/6,600-volt stations is equipped with a mimic diagram containing lamps which correspond with the high-voltage circuit-breakers, and which glow red, green, or white when the circuit-breakers in question are closed, opened, or automatically-tripped, respectively. The panels also contain two high-tension voltmeters and a carbon-monoxide indicator and alarm-lamp with re-setting switch, as well as a visibility-indicator and various signalling-relays and signalling-circuit fuses. The central panels for the Taylor street and New Quay stations also have mimic diagrams, with semaphore-type position-indicators for the isolating switches, and on each panel are mounted two low-tension voltmeters. The fan-unit panels each contain a control-switch and indicating lamp for the high-voltage circuit-breaker, low-speed and high-speed ammeters, two-way start-and-stop switches for both low- and high-speed windings, a fan-speed indicator, a two-way switch for fan-speed control, a signal-relay, and fuses for the battery, signalling, and circuit-breaker alarm-circuits.

The eleven-panel semicircular recorder-board contains a central panel which gives indications and records, relating to the three pumping-stations situated at mid-river and on opposite sides of the river at George's Dock and Morpeth Dock. The panel contains a set of instruments for each station, comprising a 400-volt voltmeter, water-measuring instruments, including a 12-inch diameter indicator showing the instantaneous rate of flow of water, a cyclometer-type continuous water-flow integrator totalling the discharge, a 12-inch wide, 1,000-hour three-pen recorder for the flow of water from the three pumping-stations, and a depth-indicator, together with a depth-indicator alarm-relay and switch, and a number of fuses. Above the panel is placed a mimic diagram of the tunnel fitted with indicating lamps for each of the three pumping-stations, and also fitted with a further indicating lamp for each of the four "portals" or entrances to the tunnel.

To the right and left of the central panel are separate panels respectively for the Liverpool and Birkenhead ventilating-stations, each panel containing either a double- or triple-scale air-flow recorder, a visibility-recorder, and a carbon-monoxide recorder. The two outer panels on each side are for the portals and for metering. The former each carry two fog-detector recorders and a vehicle-counter and recorder, whilst the latter each carry a summation-meter which

integrates the units used and shows the maximum demand for all energy consumed by the Liverpool and Birkenhead stations respectively.

The air-flow recorders register the amount of air passing through the exhaust- and fresh-air ducts. Circular impact-plates placed in the cross section of these ducts are connected through pivoted arms to the air-flow transmitters, in which the pressure-difference received from the impact-plates is converted to suitable electrical potential-differences which operate the indicator and the recorder. Indicators are fitted in the cubicle in each ventilating-station, separate air-flow meters and indicators being provided for each air-duct except in the case of the Woodside blowing-shafts and the Taylor street exhaust-shafts, where the two ducts are so arranged that only one record is required. The indicators are connected up with the chart-recorders on the control-board.

The visibility recorder automatically observes the clearness of the air in the tunnel. The apparatus consists of a beam of light which is projected upon a light-sensitive cell. Smoke or fog in the tunnel affects the intensity of the effect on the cell, and by a suitable electrical apparatus this is indicated upon a graduated dial.

The carbon-monoxide recorder registers continuously the percentage of carbon-monoxide gas in the air of the tunnel. The action of the measuring apparatus depends upon the fact that when air containing a small proportion of carbon monoxide is heated in the presence of certain "catalysts," the carbon monoxide combines with the oxygen in the air to form carbon dioxide, and this action is accompanied by an access of heat which is proportional to the original concentration of the carbon monoxide in the air. The rise of temperature under these conditions is measured by means of thermocouples, and is shown on the indicating or recording instrument as a percentage of carbon monoxide. The indicators are designed to read from zero to 6 parts of carbon monoxide per 10,000 parts of air, and to be accurate within 0·0015 per cent.

The two vehicle-counters on the recorder-switchboard add up the impulses which are received from the two Liverpool and the two Birkenhead entrances of the tunnel respectively, and which correspond with the number of vehicles entering and leaving the tunnel. The automatic counting by light-sensitive apparatus of the vehicular traffic passing through the tunnel is carried out by each line of traffic intercepting a beam of light which is projected downwards from overhead. It passes through a tubular hole in the roadway and falls upon a light-sensitive cell mounted in the ventilating channel which runs under the road, and which is connected to its associated relay-circuits in a cast-iron box mounted in the walls of the tunnel. Each

vehicle which passes intercepts the light-beam, and each interception causes a small local relay to close which operates a counting mechanism in the control-room.

Where there is a single line of traffic in and out, these counting impulses are transmitted directly to the control-room, but where there is a double line of traffic, the impulses in each direction are added together, before transmission, by summating apparatus mounted side by side with the relay circuit-boxes in the walls of the tunnel. Thus, even if two "in" vehicles enter simultaneously, each causing the closing of the local relay connected to its own light-sensitive apparatus, these two simultaneous entries are dealt with by the summating apparatus and transmitted as two impulses to the central control-room. In the control-room itself summators are mounted, on which are finally registered on a dial the total "in" and "out" traffic at the Liverpool and Birkenhead ends of the tunnel. In this way, a record is automatically kept of all the vehicular traffic.

The light-beam height-gauges are very similar in principle to the counting apparatus, although different in construction and intention. At each entrance to the tunnel, a sharply-defined beam of light is projected horizontally across the roadway from a projector-lamp, and falls upon a receiver containing a light-sensitive cell placed opposite to it and connected to a cast-iron box containing the valve- and relay-circuits. The beam of light is filtered by passing through a screen of yellow glass, and a similar screen is also placed in front of the receiver, so that in foggy weather the scattering of the light is reduced as much as possible; the beam then becomes less noticeable at night, and the receiving cell is protected from the white light which is diffused by the fog during the day-time.

Each vehicle, as it approaches to pay its toll at the toll-booths, has to pass under this beam, and if it intercepts this beam of light the sudden darkening of the receiving cell causes a signal to be given in the toll-booth, so that the attendant receives warning before the vehicle is allowed to pass into the tunnel of the permissible height being exceeded.

As vehicles approach the toll-booths they pass over weighing machines so adjusted that should the load on a wheel of a vehicle exceed 8 tons, a bell automatically rings and gives warning to the toll-keeper to refuse entry into the tunnel.

Equipment.

Lighting.

Great simplicity of effect has been obtained throughout the main and branch tunnels by the provision of sunk lighting-fittings. These

are contained in boxes recessed into the concrete filling, so that the face of the fitting is flush with the finished surface of the tunnel. The fittings are at 20-foot intervals along each side of the tunnel, and, in order to avoid the possibility of a complete lighting-breakdown, the lights are connected to three distinct supply-circuits. Lights are connected alternatively to two different circuits from each side of the river, and in the event of a simultaneous breakdown in both these, there is a supply available for every tenth light from the third circuit. Each light is of 150 watts, the whole scheme giving an illumination of from 1·5 to 2·0 foot-candles on the centre-line of the roadway.

The plazas at the four entrances are equipped with lantern fittings to blend with the ordinary street-lighting, with the addition, at Haymarket and Chester street, of large lights on the ornamental columns. Special parapet-lamps are placed along the tops of the retaining walls to the tunnel-mouth, with the addition of recessed lights similar to the tunnel-lights in the walls near the portals.

As traffic has to pass rapidly from the open air, possibly under sunny conditions, into the artificially-lighted tunnel, additional lighting is provided near the tunnel-entrances so that the driver's eyes may become accustomed to the new conditions. This is obtained by reducing the spacing of the recessed lights for a length near each tunnel-mouth, and prevents a feeling of sudden darkness on entering the tunnel, or of excessive glare on leaving it, without the necessity for providing excessively strong lighting through the whole tunnel.

The lighting for the air-ducts and other spaces in the tunnel below the roadway is divided into sections, with push-button control, so that each section can be lighted independently as required from the various points of access. Duplicate circuits for the supply are provided. The whole of the general lighting can be controlled, and the alternative sources of supply brought into use, from each of the six ventilating-stations. If necessary the whole system can be fed from a single source of supply. In addition to the ordinary road-lighting, lights are required for the traffic- and fire-indicators, gauges and auxiliary passages.

Fire- and Traffic-Signals.

At intervals of 150 feet along the length of the tunnel recesses have been formed on alternate sides for telephone and fire-alarm stations. The telephone enables the men on patrol duty to get into communication with the control-room, and beside it there is a fire-alarm available for the use of anyone who breaks the glass and pushes the button. The box also has a call-lamp which illuminates an amber

window, and so calls the patrol-man's attention to the fact that he is required to speak to the control-operator on the nearest telephone. At each fire-alarm station there is a supply of sand and chemical extinguishers, and also a fire hydrant. Immediately over each fire-station there is a floodlight which directs a beam of light on to the telephone box and so makes its position conspicuous.

For fire-control the tunnel is divided into six sections, and the telephone and fire-alarms are grouped accordingly into these sections. Emergency signs are placed at each traffic-way at the beginning and end of each section, and consist of neon letters forming the word "STOP." The letters are duplicated, the duplicate letters being connected to different sources of electric supply so that, in case of failure of one supply, one word "STOP" would still be illuminated.

These signs are operated automatically when a fire-call is put in, and thus close the section in which the fire has occurred until such time as the "all clear" is given; the sign can be put to normal from the control-room. A diagram of the tunnel showing each section is placed on the telephone and fire-alarm board in the control-room, and indication is given by an illuminated lamp which shows the section from which the call has come. In addition to closing the section of tunnel to traffic, the "STOP" signs automatically close all the corresponding toll-booths and so prevent further traffic from entering the tunnel until the "all clear" signal is given.

Traffic-signs are placed at the junction of the Liverpool main and branch tunnels, and also at the junction of the Birkenhead main and branch tunnels, and automatically regulate the traffic by red, amber, and green lights in a similar manner to that adopted in busy streets. "Stop-engine" signs are placed at each fire-station position, and are operated from the control-room. The signs, which, when illuminated, read "Stop your Engines," will only be put into operation in case of emergency, when it is required to keep the fumes from the engines becoming unduly uncomfortable or dangerous, and will only be used until the tunnel can be cleared on the instructions of the patrols.

Drainage.

The cast-iron lining, with its grouting and caulking, has been successful in reducing the inflow of water to about 26 gallons per minute, an almost negligible quantity and one which compares very favourably with the inflow of water to other tunnels. In addition to this amount, water collects in sumps at the portals from the sloping entrances in wet weather and the surface of the roadway and the interior of the tunnel have also to be cleaned periodically. Seven drainage-pumps have been installed, one at each entrance, one near

the George's Docks shafts, one near Morpeth Dock emergency shaft, and one (the largest) at the lowest point of the tunnel. The pumps are of the self-priming vertical-spindle type and vary in capacity from 200 gallons per minute to 500 gallons per minute. The maximum head is 220 feet in the case of the mid-river pump. The control of the pumps is automatic, but in addition electrical connection has been made to the control-room so that the conditions at each station are known there.

Minor Equipment.

In addition to the fire-fighting and other appliances installed in the tunnel, mobile equipment consisting of a breakdown-wagon, a cleaning-machine and a tower-wagon has also been provided, and is housed in a garage constructed alongside the New Quay ventilation-building.

Costs.

The costs of the works only have amounted to approximately £5,633,000, made up as follows :—

	£
Pilot-headings	448,600
Main tunnel under the river	1,858,300
Tunnels in Liverpool	837,000
Tunnels in Birkenhead	1,035,000
Pumping	101,000
Cementation	153,000
Ventilation-connections from the surface of the ground to the tunnels	247,000
Ventilating fans	61,700
Driving-gear and electrical equipment	99,800
Special foundations for ventilation-buildings	91,100
Ventilation-buildings	532,500
Electric cables	32,500
Minor equipment	32,200
Finishings to the tunnels	103,300
	£5,633,000

The unit costs and the approximate quantities of the more important items of the work are as follows :—

Excavation in shafts, in rock	9,000 cubic yards	43*s.* to 47*s.*
Excavation in headings, in rock	120,000 ,,	42*s.* 6*d.*
Excavation in tunnel, in rock under the river	267,000 ,,	41*s.* 6*d.* to 42*s.* 6*d.*
Excavation in tunnel, in rock under the land	382,000 ,,	30*s.* to 32*s.* 6*d.*

Excavation in trench, in soft ground	22,000 cubic yards	12s. to 21s.
Excavation in dumpling, in soft ground	40,000 ,,	7s.
Excavation in trench in rock . .	17,000 ,,	12s. 6d.
Cast-iron lining in shafts . . .	770 tons	£7 10s. to £8.
Cast-iron lining in tunnel . . .	80,000 ,,	£9 10s. to £15.
Grouting, including hand-packed spalls	123,000 square yards	12s. to 19s. 6d.
Bolts and nuts	51,000 cwt.	24s. to 32s.
Lead caulking (per ton of iron) .	—	6s. to 12s.
6-to-1 concrete in side-walls . .	15,000 cubic yards	43s. 6d. to 52s. 6d.
6-to-1 concrete between steel ribs	7,000 ,,	75s. to 80s.
10-to-1 concrete-filling to cast-iron segments, 12 inches thick .	53,000 square yards	24s. to 35s.
Reinforced concrete in roadway .	51,000 cubic yards	72s. to 90s.
Shuttering	260,000 square yards	9s. to 20s.
Steel reinforcement in roadway .	4,600 tons	£14 to £17.
Cast-iron roadway	46,000 square yards	16s. 9d. plus 10 per cent. for services of main contractors.
Cement-gun rendering 1 inch thick to roof	76,000 ,,	7s. to 8s. 6d. for cement work only, plus 10 per cent. for services of main contractors.
Glass dado	19,200 ,,	21s. plus 10 per cent. for services of main contractors.
Steelwork in arched ribs (excluding the junction chambers) . . .	1,415 tons	£21 to £23.

The cost of the scheme, including land, easements, and fees, has amounted to approximately £6,648,000. This figure is considerably larger than the estimated cost of £5,222,000, as both the land and the works cost more than was anticipated. The increase as regards the works is due to the tunnels being lengthened to suit the positions of the entrances as they were finally decided upon, and to the ventilation. At the time when the original estimates were prepared there was no experience available regarding the cost of ventilating a tunnel to take modern road-traffic. In addition, building requirements were imposed in connection with some of the ventilation-stations that were quite beyond any reasonable assumptions that could be made at the time of estimating. The Ministry of Transport has made a grant of £2,500,000 towards the cost. The balance, together with the cost of operation and other expenses, has been met by loans. The charges for the loans are being met out of the receipts from the tolls that are charged and out of rates levied upon Liverpool and Birkenhead. The tolls average 1s. 8d. per vehicle, and the yield has been

greatly in excess of the estimates. During the first year of operation, 3,063,923 vehicles used the tunnel, and the income from tolls amounted to £250,143 9*s*. 10*d*. The total of 3,063,923 vehicles was made up of 2,543,650 motor-cars and lorries, 142,124 motor-cycles, 47,368 motor-cycles and sidecars, and 330,681 pedal-cycles.

Technical Advisers, Staff, and List of Contractors.

Sir Basil Mott, C.B., F.R.S., Past-President Inst. C.E., was appointed Engineer for the work by the Mersey Tunnel Joint Committee in 1925. His partners, Mr. David Hay, M. Inst. C.E., and the Author, acted in close collaboration with him throughout and acted on his behalf at various times during the construction period, which lasted from December, 1925, to July, 1934. The late Mr. John A. Brodie, Past-President Inst. C.E., for many years the City Engineer of Liverpool, was associated with Sir Basil Mott as Joint Engineer. The Architect appointed by the Joint Committee to design the ventilation buildings was Mr. Herbert J. Rowse, of Liverpool.

Many special problems arose, and the following experts were called in by the Engineers to assist them: Professor P. G. H. Boswell, D.Sc., F.R.S., on geology; the late Professor J. S. Haldane, C.H., D.Sc., F.R.S., and Professor Douglas Hay, M.C., B.Sc. (Eng.), M. Inst. C.E., on ventilation; Dr. Oscar Faber, O.B.E., M. Inst. C.E., on reinforced-concrete roadway-design; Mr. P. J. Robinson, M.Eng., City Electrical Engineer of Liverpool, on electrical matters; Mr. E. W. Monkhouse, M.V.O., M.A., M. Inst. C.E., on vibration problems; Mr. Herbert J. Rowse on architectural treatment.

The staff on the site was a large one, and was headed by the late Mr. B. H. M. Hewett, M. Inst. C.E., who acted as Engineer-in-Charge until his death in November, 1933. The Resident Engineers were Mr. John F. Hay, Assoc. M. Inst. C.E., from 1926 to November, 1930, and Mr. C. B. H. Colquhoun, B.Sc.(Eng.), Assoc. M. Inst. C.E., from November, 1930, to the completion of the works.

The contractors for the river-tunnel and Liverpool land-tunnels were Messrs. Edmund Nuttall, Sons & Co., Ltd. The land-tunnels at Birkenhead were constructed by Sir Robert McAlpine & Sons. Messrs. Nuttall were represented on the works by Mr. P. W. Bertlin, M. Inst. C.E., and Mr. E. J. Hambly. Sir Robert McAlpine & Sons' representatives were Mr. W. M. Shaw, the late Mr. J. M. Neilson, and Mr. J. H. Wallace.

The fans were supplied by Messrs. Walker Brothers (Wigan), Ltd., and by The Sturtevant Engineering Company, Ltd., of London. The electrical motors and equipment were manufactured by the

Metropolitan-Vickers Electrical Company, Ltd. The electrical cables were supplied by the Mersey Cable Works, Ltd. In addition, there was a large number of contractors for the various subsidiary works and for the ventilation-buildings.

The work has been of a long and complicated nature, and to all who have been associated with it the Author would express the very great appreciation that all the partners in his firm have of the skill manifested and of the loyalty and devotion to duty that have been so freely given, and which have made this monumental work the success that it is. He would also like to take the opportunity of expressing the great regret of all connected with the work that Mr. Hewett did not live to see the completion of the scheme on which he was so long engaged and into which he put so much thought and skill.

The Paper is accompanied by thirteen sheets of drawings, from which Plates 1, 2, and 3 and the Figures in the text have been prepared.

Fig. 11.

MECHANICAL ERECTOR FOR 44-FOOT IRON.

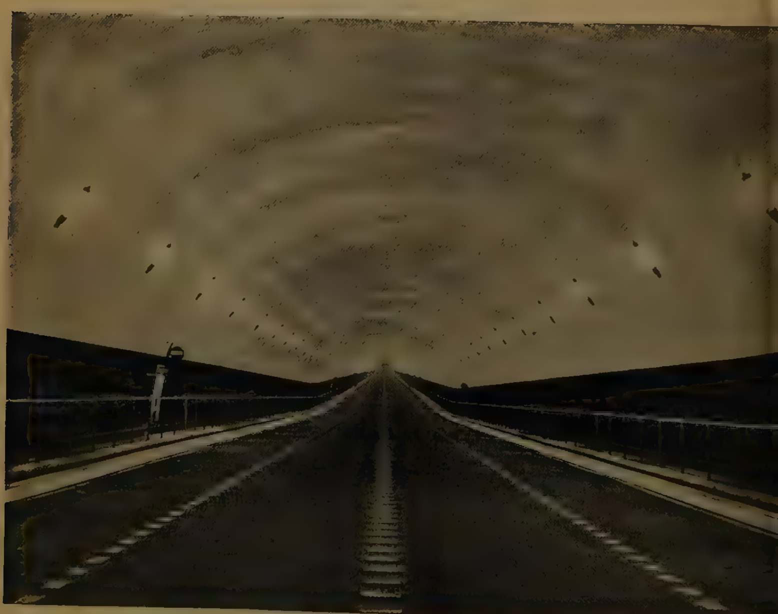
Fig. 12.

EXPERIMENTAL ROADWAY-SECTION.

Fig. 13.

TEMPORARY SUSPENDED ROADWAY IN 44-FOOT TUNNEL (RIVER SECTION).

Fig. 14.



FINISHED TUNNEL.

Discussion.

The AUTHOR showed a number of slides illustrating the work described in the Paper, some of which were reproduced in *Figs. 11* ... *14*. The Author.

In connection with the paving of the roadway, he would mention that the whole question of the paving had received a great deal of attention. Asphalt, granite setts and various other materials were considered, but, in view of the fact that the traffic ran almost in grooves, and hardly deviated more than a few inches to one side or the other, it was finally decided to adopt cast-iron setts. They had proved very successful, as skidding was almost non-existent, except when vehicles entered the tunnel while it was raining. However, he believed that a thoroughly satisfactory paving had been obtained, and he thought that it was one which was likely to give a very long life. It had taken on a certain amount of polish, but so far there was no wear to be seen.

As was no doubt inevitable in the case of a scheme which was spread over so many years, death had taken its toll of quite a number of those who had been associated with it. Sir Maurice Fitzmaurice, Past-President Inst. C.E., who had been associated with the preparation of the initial report, died before construction commenced. Half-way through the period of construction the death of Sir Archibald Salvidge occurred; it was due to Sir Archibald's initiative and driving-power that the scheme was initiated. Some 9 months before the tunnel was opened to traffic Mr. B. H. M. Hewett, M. Inst. C.E., the engineer in charge of the works, also died. His death was a very great loss to the Author's firm; Mr. Hewett was a man of great experience who had done invaluable work, and it seemed a tragedy that he should not have lived to have seen the conclusion of the great work on which he was engaged. Mr. Anderson felt that Mr. Hewett, rather than himself, should have presented the Paper to the Institution. In some ways it was impossible not to feel that Mr. Hewett's death was due to the tremendous amount of work that he had done. On behalf of Sir Basil Mott and the other members of his firm, Mr. Anderson wished to pay that tribute to Mr. Hewett's memory.

They also recognized that Mr. Hewett was not the only one who had given of his best in connection with the work, and he had been expressly asked by Sir Basil Mott to take the opportunity of thanking all those who had helped, advised and guided them, as well as all

The Author. those who had served them. Sir Basil Mott had particularly wis it to be emphasized that, although he was looked upon as engineer, the undertaking was the result of team-work on the p of all concerned. On his behalf, Mr. Anderson had great pleas in thanking everyone who had been associated with the undertaki

Sir Charles Bressey. Sir CHARLES BRESSEY remarked that he had one qualification taking part in the discussion, namely, that, acting on behalf of Ministry of Transport, he had had various opportunities of see the operations in progress during the construction of the work. was one of those who, like the Author, had walked along the bott of the 44-foot tube, and he did not know of anything more pressive, except perhaps the sight he had had a year or two ago the airship "Hindenburg" during construction; the airship ha much larger diameter than the tunnel, and in its great shed Friedrichshafen seemed very nearly as impressive.

A great part of the Paper was devoted to the subject of ventilati which was an indication of the extraordinary difficulty that t particular aspect of the work had presented. The cost was v high, but it was not altogether fair to take the figures at their fa value, owing to the enormous addition which had been made to cost by the exigencies of local amenities. He hoped that th would not be many other tunnels built where the cost under t heading would be quite so high.

The traffic statistics given in the Paper were of particular inter and were satisfactory, as the number of vehicles, which was c 3,000,000 per annum, was greatly in excess of the estimate. Altho that number might seem a large one, it did not represent very de traffic, and the tunnel was probably capable of carrying two or th times that flow. The promoters of the tunnel, if they had misgivings on financial grounds, could look forward to better ti when the traffic figures might be doubled or trebled.

The ventilation was very effective, and on frequent occasions air in the tunnel appeared to be cleaner and fresher than the out atmosphere. The particulars of the ventilation-system given in Paper would be of great interest to those who were concerned w subsequent tunnels, and particularly, no doubt, with the tu which was shortly to be constructed under the Thames betw Dartford and Purfleet.

Mr. Frank. Mr. T. PEIRSON FRANK felt sure that all present would wisl congratulate the Author and all those associated with him on completion of such a splendid national undertaking. There been a number of tunnel-projects recently; members of Mr. Fra own staff had been engaged upon the preparation of reports some of those projects, and they had been considering some impr

nts in connection with the Thames tunnels. He imagined that Mr. Frank. experience gained at Liverpool would prove helpful when some he newer projects were translated into reality.

Vhen the Mersey tunnel was first proposed, the intention was to sh the tunnel, both in Birkenhead and in Liverpool, at points ore the present entrances were reached, and he presumed that the s given in the first instance referred to the scheme as originally posed; at any rate the actual costs showed a tunnel rather more n 900 yards longer than that originally placed before Parliament. mentioned that fact because he had already described the work national one, and it would be seen that the contribution from Ministry of Transport was £2,500,000; he submitted that that not sufficient for a work such as the Mersey tunnel, and if the nt he was making had never been put to the Ministry he hoped t it would be placed before them. He held a post in Liverpool he time that the work was carried out, and he had been appalled the prospect of all the traffic which would eventually use the nel being discharged at the point at which it had at first been posed to discharge it. The cost of the necessary street-improvents would have been enormous, and, moreover, the traffic-culties would have been considerably increased. On those unds he felt that there was good reason to ask for an increased nt towards the cost of the tunnel.

he figures on p. 515 of the Paper gave a daily average of 7,488 icles a day, excluding pedal-cycles. It was difficult to make comparisons with the Mersey tunnel, but he wanted to make h comparisons as were possible; in the case of the Blackwall nel, which had a carriageway only 16 feet wide, during 12 rs of a day in the summer of 1935 when a census was taken, re were 7,712 motor- and horse-drawn vehicles. Cycles were included in that census. The maximum speed in that tunnel restricted to 8 miles per hour, which was not always attained account of the horse-drawn vehicles. It would be clear, there-, that in the case of the Mersey tunnel provision had been made considerable expansion. He had no doubt that that expansion ıld come more rapidly than might be expected; in the case of Blackwall and Rotherhithe tunnels, of which the carriageway in h case was 16 feet, the traffic had doubled within the last 7 or ears.

n the section of the Paper dealing with ventilation, he noticed t the maximum dilution had been taken as 2·5 parts of carbon noxide per 10,000 parts of air. In the case of the smaller tunnels n which he was associated—they were each only $1\frac{1}{5}$ mile long—the eavour was made to work to 2 parts per 10,000, but he did not

Mr. Frank. say that that was always adhered to, on account of the increas the traffic and the delays caused by horse-drawn vehicles.

If the tunnel were being constructed again, it would be of inte to know whether the Author would suggest adopting the twin tunn referred to in connection with the Holland tunnel. He put question on the ground of convenience in regard to ventilat although he could see that there were disadvantages from the p of view of the traffic. It would be of interest to know how section of rubber-surfaced roadway had been found to respond the traffic through the tunnel. Presumably, the traffic was usu operated under what might be termed dry-weather conditions, some of the difficulties in regard to skidding which had been recen discussed [1] might arise if the cast-iron road became wet.

With regard to the "run-in" described on p. 485, he happened t on the top of it when the first explosion occurred, and he mentio it because, whilst precautions were taken in connection with water-mains, it was the gas-main which might have given rise more serious trouble through the gas collecting in underground p or sewers. His staff had had to lay a sewer on the north side, un what was described in the Paper as the foundations of he buildings. They had tried to get the tunnel-authorities to do but had been unsuccessful and had had to carry out the work direct labour.

He had had the opportunity of inspecting the work from tim time, and he much appreciated those opportunities. He had not that a small settlement was caused when the shield was at w They had waited for a long time to renew the tramway-track Dale street, which was over the tunnel, and in the end they had to reconstruct them and to re-pave the street prior to the tu being driven under it. He then noticed a small settlement a the tram-rails, which extended for some time, but was relati small. He thought that that might be avoided in future if so what similar ground had to be excavated by special attention b directed to the excavation near the crown of the shield. W regard to the cementation-process, he would like to know w pressures were originally instituted and what were used after s little headway had been made along the length of the tunnel.

He would like to add that not all the spoil was carried to wa it had been possible to use a great deal of the excavated rock in construction of a river-embankment some little distance from

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[1] R. G. C. Batson, G. Bird and R. E. Stradling, "Road Engine Problems: Judging the Slippery Road," Journal Inst. C.E., vol. 2 (193 p. 443 (April, 1936).

e, where some 65 acres were ultimately to be reclaimed from the Mr. Frank.
er.

Mr. G. G. LYNDE congratulated the Author on his Paper. The Mr. Lynde.
rsey tunnel presented a new problem, namely, that of magnitude.
referred principally to the river-section; it was only the river-
tion where the full circle was used, and where that problem
s presented in the most acute form; that section of the tunnel
s 1 mile from shaft to shaft, and was of such a size through-
t that it would be possible to build inside it a three-storey house
mplete with foundations and chimneys. In the portion under
buried channel the top heading was lined with tube-iron, and
London tube looked relatively tiny compared with the tunnel.
interesting point which might be mentioned was that many
ologists had long believed that in glacial times the Mersey flowed
the direction opposite to that in which it now flowed, and proof
that theory had been discovered.

The problem of magnitude was not only one of dealing with a
ge quantity of material in a small space, but was also one of the
ual size of the tunnel itself. He had no hesitation in saying that
exceedingly wise decision, taken by the engineers, to construct
top part of the tunnel first was one of the most important de-
ions in the construction of the work. It enabled the bottom
ading to be used for continuous traffic, and when there were five
reak-ups" between the two shafts under the river, with ten faces
rking and almost continuous shot-firing, there would have been
lless delays if the traffic had had to be taken through the "break-
s." As it was, the traffic went on uninterruptedly in the bottom
ading while the arch was being constructed. Another important
ision was the construction of the suspended roadway, which
ried three lines of traffic. Over that suspended roadway, traffic
sed continuously day and night while the invert was being
structed. The excavation under the river amounted to about
00 tons a week, and rose to a peak of 7,000 tons per week; the
erpool shaft, which dealt not only with the river but with part
the Liverpool approach, had a peak of 7,000 tons a week, which
ant one wagon per minute lifted 130 feet from the bottom of the
ft to the tipping-stage. That was done by a series of high-speed
s, which proved very satisfactory for their purpose. The arch
been built, and the invert had been put in, without any trouble,
, looking at the finished tunnel, it seemed as if there had been
difficulties during the construction. A great deal of anxious
ught had, however, been necessary before the various decisions
been reached.

He would like to refer to the construction of the junction-chamber

Mr. Lynde. under Dale street; it was a large chamber 66 feet long with arch-span of 51 feet. It was entirely constructed in tunnel, 7,600 cubic yards of excavation were taken out of it. It was c structed by driving headings 6 feet wide and 25 feet high, all rou the four sides, and those headings were filled with concrete became the walls. Headings 4 feet wide were then driven across which steel ribs were placed and concreted up, so that the arch gradually formed; the dumpling was then removed.

He would like to mention the excellent work done by the Robert Guthrie and the late Frederick Budden, successive walk gangers, and by the night-walking ganger, William Lawrence. would also like to draw attention to the fine qualities of the m employed on the work; their resourcefulness was demonstrated the case of the "run-in" mentioned on p. 485, where their pron and plucky action prevented what might have been a very seri mishap. The men who drove the drainage-channel also deser mention. Very little had been said about that channel, which driven 1,500 feet out under the river at a depth of 170 feet bel high water; it was 7 feet in diameter and produced 4,000 gall of water a minute. Those men worked under appalling conditio but they did their job well.

He could add little to what the Author had said regarding Hewett, who had brought to the work great experience and wisdo The success with which the work was carried out owed much to regular meetings between engineers and contractors at which various difficulties were freely and fairly discussed. The leader all that team work had been Sir Basil Mott.

Mr. Colquhoun. Mr. C. B. H. Colquhoun remarked that an interesting co parison could be made between the Mersey tunnel and two ot tunnels of the same type which had recently been built, name the Holland tunnel in the United States, and the Antwerp tunn The outside diameter of the Mersey tunnel was just over 46 f that of each of the two Holland tunnels being 29½ feet and that the Antwerp tunnel being a little over 30 feet. The total numbe track-feet (namely, the length of the tunnel in feet multiplied the number of tracks) was 53,000 in the case of the Mersey tunn 37,000 in the case of the Holland tunnel, and 13,850 in the case the Antwerp tunnel; that gave some idea of how much larger Mersey tunnel was than any other tunnel of the same type. Holland tunnel was opened in 1927 and the Antwerp tunnel in 19 and comparative figures were set out in Table II. It did not app from the figures of cost per track-foot, that the total cost of Mersey tunnel was really so very great. The increased volume the ventilation-buildings for the Mersey tunnel was due to

eater length of the tunnel, together with the provision of 100 per Mr. Colquhoun. nt. stand-by plant, instead of only 50 per cent. stand-by plant as the case of the other two tunnels. The size of the Mersey tunnel compared with the other tunnels would be realized when Table II as studied.

TABLE II.—A COMPARISON OF SOME OF THE CHARACTERISTICS OF THE MERSEY, HOLLAND AND ANTWERP TUNNELS.

Characteristic.	Tunnel.		
	Mersey.	Holland.	Antwerp.
ngth from street to street: feet	15,191	9,200	6,924
ack-feet, surface to surface	53,000	37,000	13,850
itside diameter: feet	46·25	29·5	30·83
oss-sectional area: square feet	1,680	682	744
olume of tunnel-excavation: cubic yards	684,000	475,000	203,000
aximum depth below water: feet	160	110	120
st of works, excluding land and fees: £	5,920,000	7,427,000	1,800,000
st of works per track-foot: £	111	200	130
st of works per cubic yard of excavation: £	8·65	15·60	8·86
st of land, excluding fees: £	878,000	1,460,000	160,000
st of land per track-foot: £	16	40	12
tal cost, works and land (no fees): £	6,798,000	10,350,000	1,960,000
tal cost per track-foot: £	127	277	142
st of ventilation-buildings: £	510,000	750,000	128,000
st of ventilation-buildings per track-foot: £	9·6	20	9
st of ventilating plant: £	242,000	373,000	80,000
st of ventilating plant per track-foot: £	5	10	6
tal volume of air, fresh and exhaust: cubic feet per minute	10,000,000	11,521,000	2,000,000
olume of air per track-foot: cubic feet per minute	190	311	144
umber of ventilation buildings	6	4	2
ack-feet of tunnel per ventilation-building	8,166	8,368	5,800
tal volume of ventilation-buildings: cubic feet	4,418,000	2,992,000	621,000
olume of ventilation per track-foot: cubic feet	85	82	45
st of ventilation-buildings per cubic foot of building	2*s*. 3*d*.	5*s*.	4*s*. 1½*d*
oportion of stand-by ventilation plant: per cent.	100	50	50
aximum distance between ventilation-buildings: feet	4,510	3,375	2,798

The operation of the tunnel was carried out in a way which he ought was rather unusual. It had originally been expected that

Mr. Colquhoun. the Joint Committee, the statutory body responsible for the tunn would employ a complete staff of its own, but that scheme v eventually superseded by one in which the operation of the tunn was carried out by what was called the "contracting-out" syste The work of operation was divided into a number of parts, such ventilation, cleaning, and toll-collection, and each of those sectio of the work was let out by tender to the Corporations of Liverp and Birkenhead, the lower of the two tenders being accepted. Th seemed a curious method of operating the tunnel, and he would n care to say that it was the most economical or the most efficie There were one hundred and seventy-seven permanent and abo forty-five part-time employees, the latter being accountants, cler or other staff of the Corporations, who were employed part-ti on the tunnel. Assuming that the part-time employees gave h their time to the tunnel, that inferred an additional twenty-t employees, or a total operating staff of practically two hundr That might seem a very large staff, but in view of the amount traffic going through he did not consider that it was really too grea

In the first year, as stated in the Paper, over 3,000,000 vehic (including pedal-cycles) used the tunnel. The actual number motor-propelled vehicles was 2,672,000, and that was divided into approximately 33½ per cent. of commercial vehicles and 66½ p cent. of private vehicles. There had so far been an increase duri the second year, which was not yet complete, but, comparing tw representative months, September and October, 1934, of the fi year, with September and October, 1935, the number of vehic during September, 1934, was 243,000 and for September, 1935, was 268,000. In October, 1934, and in the same month of 193 the figures were 195,000 and 238,000 respectively. The decrea from September was purely due to the normal fall in traffic duri the winter. The increase was 10·3 per cent. for September a 22·0 for October, the average over the two months being 16 per cen Apparently there would be an annual increase in traffic of abo 14 to 16 per cent.

It was of some interest to investigate those figures. The Birke head ferries carried, before the opening of the tunnel, about million motor-propelled vehicles, of which about 64 per cent. we commercial vehicles and 36 per cent. private vehicles. In the ca of the tunnel the proportions had undergone a great change. Com mercial vehicles formed 64 per cent. of those using the ferries, b only 33½ per cent. of those using the tunnel. On going into t figures a little more closely, it was found that the actual increase commercial vehicles using the tunnel in the first year as compar with those using the ferries the year before was only 12 per cen

Mr. Colquhoun.

ı other words, it was the same as the annual increase which had ccurred in the first two years of the use of the tunnel, so that robably the same number of commercial vehicles would have used e ferries had the tunnel not been open. The great increase had, owever, occurred in the private vehicles. Whereas on the ferries eir percentage was 36, in the tunnel it was 66½, and the actual crease in the number of private vehicles using the tunnel in the rst year was 295 per cent. In spite, therefore, of the fact that the nnel was primarily built for commercial traffic, it seemed that it as the private traffic which was ultimately going to pay for it.

The results of the efficiency-tests and experiments which had been rried out on the ventilation-plant showed that a great deal of the orse-power involved in running the plant was used up in over-ming the friction of various bends and awkward places in the ıcts. That was a point which would, he thought, have to be given 'en greater consideration in any future tunnel than it had been in e case of the Mersey tunnel. Most of the fans which were used ere of the old centrifugal type which had been in use for the last ındred years, but at Woodside, where the buildings were not mpleted when the tunnel was opened, there were two axial-flow propeller-type fans installed temporarily. Such fans had originally en considered for use in the tunnel, but they were taken out for rious reasons, among which were lack of experience with them, ıd insufficient time for prolonged reliability-tests, as well as poor ficiency-figures and excessive noise. The experience with those opeller-type fans at Woodside, however, was that they had been nning for from 16 to 18 months night and day without a stop, d he thought that that was sufficient to show their reliability. A nsiderable amount of research-work had been carried out which d overcome their disadvantages, and he thought that the propeller-pe fan had now reached a stage when very serious consideration ould have to be given to it for future work in tunnels. Its use ould have other advantages, in that it would simplify the design ducts and would reduce the resistance, enabling less horse-power be used; in general, he thought that, in future, ventilation-ildings and plant would be much smaller and simpler than in the se of the equipment for the Mersey tunnel.

The two assumptions on which the amount of ventilation had been sed were, firstly, the amount of carbon monoxide emitted by a hicle, and secondly the amount of carbon monoxide which could permitted to be in the atmosphere of the tunnel at any time. e first figure was deduced primarily from experiments which had en carried out by the United States Bureau of Mines for the Holland nnel; the results of those experiments gave a figure of 1⅝ cubic

Mr. Colquhoun. foot of carbon monoxide per vehicle per minute. The amount t carbon monoxide which could be permitted in the tunnel atmosphe was laid down by the late Professor J. S. Haldane. Since the tunn had been opened, there had been an opportunity of determining tho figures more accurately, and it had been found that, instead of taki 100 cubic feet per hour, it was only necessary to provide for fro 55 to 60 cubic feet of carbon monoxide per vehicle per hour. Th was probably due to the greater efficiency of the internal-combusti engines used in motor-vehicles in Great Britain.

Mr. Brown. Mr. R. D. Brown remarked that 26 years ago he had come to t end of a 7-year period in tunnelling operations, and since then had not been greatly interested in tunnel-work. During the la few years, however, he had been asked by the late Mr. H. A. Re to investigate certain aspects of tunnels under the Humber a under the Thames at Dartford, and he had found it surprising th after such a long interval, the same methods were still in use, pa ticularly in regard to the cast-iron lining and the cross-section shape of the tunnel.

It was 69 years since Barlow first used a cast-iron lining in a sm tunnel which he was driving under the Thames, and, with a f exceptions, a cast-iron lining was still adhered to in Great Brita In the case of small tunnels it had great advantages in weight a permanence, but as compared with steel it was a weak and brit material, and when the segments were filled with concrete the de flanges of the iron separated the concrete into small pockets whi were of no value from the point of view of strength, but merely add dead weight. In the case of a tunnel of the magnitude of that und the Mersey, Mr. Brown thought that it would be worth while consider steel as an alternative for the lining. A thin skin could used to keep the water out during the setting of the concrete, b inside that skin there would be very strong open-work structur steel ribs, with steel reinforcing rods through the concrete bo longitudinally and circumferentially, which would give much grea strength and at the same time a greatly reduced cost. The ma structure of the lining would be embedded in concrete and wou have a great deal more permanence than cast iron, even if the th outer skin rusted away in course of time.

A beginning had been made on the Continent and in the Uni States with the use of steel lining for tunnels. The earliest referen to it which he had been able to find was in 1930.[1] The first use

[1] "The Detroit-Windsor Tunnel," *Engineering*, vol. cxxx (1930), pp. 6 667, 702.

eel in the U.S.A. was experimental and was not altogether a success, Mr. Brown.
cause it was a shield-driven tunnel and the jacks crumpled the ngitudinal member, but those difficulties had been overcome, and was now found that, from the point of view of cost, steel had nportant advantages. He had made a very rough estimate on the sis of costs ruling in 1930 for a 48-foot diameter tunnel, and on a ost conservative basis he thought a sum of £275,000 might have en saved in the construction of the Mersey tunnel had steel been ed.

With regard to shape, and particularly in the case of large air-driven nnels, it seemed to him a great pity to adhere to the circular form, was nearly always done in Great Britain. He had prepared a emorandum on those lines and had circulated it in 1931 to a number engineers and contractors, including the engineers of the proposed artford tunnel; he had been very pleased to see in the public ess recently that the large vertical diameter formerly proposed for e Dartford tunnel had now been reduced, which would permit a eat relief in the air-pressure and would considerably improve the k of balance between the air pressures at the crown and the vert. If that tunnel were driven under compressed air, he thought at, owing to its great depth in fissured chalk, it would prove one the most difficult works ever undertaken in Great Britain. ere were other methods of construction which would be safer and s costly.

Cracks had occurred in the lining of a certain tunnel many years o, and had caused great consternation amongst all concerned. culations based on certain assumed data were then made and re taken to Sir Benjamin Baker, Past-President Inst. C.E. When Benjamin looked at them, he said, "It would be quicker to assume thickness than to assume the data." He added that the thick- s for the 26-foot diameter Blackwall tunnel was "assumed" at iches under the river and 1½ inches under the land.[1] Perhaps the thor would amplify his valuable Paper by giving some of the sons which led to the adoption of a skin-thickness of 1½ inch in case of the Mersey tunnel.

IR. J. L. HODGSON associated himself with previous speakers Mr. Hodgson.
complimenting the Author and his firm on the very great ineering achievement which they had carried out so successfully. part from his work on air-measurement in connection with the tilation of the tunnel,[2] there were two points to which he desired efer. The first dealt with the glacial channel which Professor

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[1] Minutes of Proceedings Inst. C.E., vol. clxxxi (1909–10, Part III) p. 227.
[2] Mr. Hodgson's remarks on that subject will be published in the Corres- ence on the Paper.—SEC. INST. C.E.

Mr. Hodgson. P. G. H. Boswell, from his great knowledge of the local effects glaciation, had been able to say ran in the opposite direction to river along the present course of the Mersey. Professor Bosw had thus been able to save the Tunnel Committee many thousa of pounds. The channel had been found when the Mersey Railw tunnel was driven in 1884, and it had been assumed that it would deeper at the site of the road-tunnel, which was situated nearer t sea. Professor Boswell, however, was able to show that it would a certain amount higher.

In connection with the general subject of glaciation, Mr. Hodgs desired to draw attention to a book by Mr. H. E. Forrest,[1] a fie naturalist, in which was correlated an immense amount of biologi and geological data. Mr. Forrest, in an attempt to explain w certain forms of plant and animal life were common rather Ireland and North America than to Ireland and England, had be led to study the ice-markings and glacial deposits, as well as t contours and composition of the ocean-bed throughout the Nor Atlantic area. That study had led Mr. Forrest to the conclusi that, in Pleistocene times (about 1,000,000 years ago), much of t bed of the Atlantic, including Iceland, had been some 12,000 fe higher than at present, and that that high land had given rise to ice-sheet. That ice-sheet, emanating from Iceland (then abo 17,000 feet high), had had sufficient pressure behind it, with mean gradient of about 17 feet per mile, to force its way over t mountains of Ireland and the Isle of Man, as far as the Shannon a Thames valleys. Whether the particular deductions of Mr. Forr were correct or not, the whole question of glaciation was one wh should be of great interest to members of The Institution, as the i sheet, when it melted (from 30,000 to 10,000 years ago), deposit gravels, sands and clays, and eroded channels, which almost eve where in Great Britain affected the work of the civil engineer.

The other point to which Mr. Hodgson wished to refer dealt w the financing of the tunnel. As was usual in such cases the inter and sinking fund amounted to three times the money loaned enable the tunnel to be built by the engineers, 3¾ per cent. per ann having to be paid for a period of 80 years.

Mr. Hodgson then showed a cinematograph film of the construct of the tunnel.

He then quoted the following words which His late Majesty K George V used at the opening ceremony, and which set the seal Royal approval upon such activities as tunnel-making :—

"... a thoroughfare so great and strange as this Mersey tunnel now made ready by your labour.

[1] "The Atlantean Continent" (Second Edition), London, 1935.

"Who can reflect without awe, that the will and power of man can drive tunnels such as this, wherein many streams of traffic may run in light and safety beneath the depth and turbulence of a tidal river bearing the ships of the world? Mr. Hodgson.

"May those who use it ever keep grateful thought of the many who struggled through long months against mud and darkness to bring it into being.

"I praise the imaginations that foresaw, the minds that planned, the skill that fashioned, the will that drove, and the strong arms that endured. . . .

"Such a task could only be achieved by the endeavours of a multitude.

"May our peoples always work together thus for the blessing of this kingdom by the wise and noble use of the power that Man has won from Nature.

"I thank all those whose efforts have achieved this miracle."

Dr. W. L. Lowe-Brown congratulated the Author on his Paper. Dr. Lowe-Brown.
ıe truly national character of the Mersey tunnel was recognized by is late Majesty King George V, who opened it, and by Her Majesty ıeen Mary, who allowed it to be called Queensway.

The late Mr. Hewett, the Engineer-in-Charge, had been one of :. Lowe-Brown's most intimate friends. Dr. Lowe-Brown had d many opportunities of visiting the tunnel with Mr. Hewett, so at he was familiar with most of the work described in the Paper. ırther, Sir Basil Mott had given him the opportunity of being ectly connected with the work, as when certain modifications of e design of the cast-iron lining were under discussion, Sir Basil d asked him to make the calculations for the modified design.

The Author was to be congratulated on having covered so much ound in the length of an ordinary Paper, but Dr. Lowe-Brown t sure that the Author would be the first to acknowledge that he d had to omit a great many particulars. He would like, therefore, suggest that the Author might allow members of his staff, or ıers connected with the work, to write a series of Papers putting record all the important details which would be of use to other gineers.

In the short section of the Paper devoted to the history of the ject there was nothing with regard to what was nowadays called lanning." The reasons why a 4-track tunnel was adopted instead two 2-track tunnels might be known to many, but Dr. Lowe-own would suggest that some reference should be made to them the Author. Another subject which had been referred to, and ich had been touched upon by the Author, was geology. Before

Dr. Lowe-Brown.

the headings were driven, Professor Boswell had forecast the natu of the rock which would be passed through and the position of t faults which would be met, and that forecast was found to be ve accurate. During the construction, much additional informati was obtained with regard to the Upper and Middle Bunter Sandsto beds, such as the amount and level of water contained in them, t differences of water-level across the faults, and the effect of t construction of the Mersey tunnel on the pumping in the Mers railway tunnel. There were many questions connected with t construction, such as excavation-methods, cementation-metho caulking experiments and difficulties of grummeting about whi information might with advantage be given by the Auth Some account of the numerous kinds of interior finish that we investigated, and the reasons for the adoption of the type describ in the Paper, would also be of interest.

The most important question of all was probably that of ventilatio Extensive researches had been made on the various systems ventilation, and some particulars would be most useful. T Americans had published a considerable amount of detailed inform tion on the results of their experiments, particulars of which mu have been most helpful to the engineers of the Mersey tunnel as starting point for their researches. In the section headed "Ven lation" the Author stated: "The maximum dilution has be taken to be 2·5 parts of carbon monoxide per 10,000 parts of air times of peak traffic; under ordinary conditions it will be well bel this figure." In the American tunnels, the maximum amount carbon monoxide permissible was 4 parts per 10,000 in times peak traffic, but the actual amount of pollution never reached th figure. Further, in a pamphlet[1] previously published by t Mersey Tunnel Joint Committee it was stated that 2·5 parts p 10,000 would be the maximum pollution under ordinary conditio but that this might be increased to 4 parts in times of extreme pe load. Perhaps the Author would make that point quite cle because, if it had been found necessary to adopt a much hig standard of purity in England than in America, it would be interesti to have some attention drawn to that fact.

Reference had already been made to the streamlining of the a ducts and the losses in the bends, but he felt sure that furt information was available; he asked the Author to allow it be made public. Mr. Colquhoun had already referred to the questi of cost, so that it was unnecessary to say more on that point, beyo

[1] "The Story of the Mersey Tunnel, officially named Queensway," Lond 1934.

e fact that the Mersey tunnel had been built very cheaply compared Dr. Lowe-Brown.
th most other tunnels.

Mr. N. G. Gedye associated himself with previous speakers in Mr. Gedye.
ngratulating the Author and his colleagues on the magnificent rk which they had carried out. In 1931 he visited and investigated some detail the construction and operation of two of the sub-ueous vehicular tunnels in the United States, namely, the Holland nnel under the river Hudson, and the tunnel beneath the Detroit er between Windsor (Canada) and the United States. The Author ted, in the section headed "Ventilation" (p. 492), that in the olland tunnels there was a longitudinal movement of air induced the passage of traffic in one direction, but Mr. Gedye's experience s that there was practically no longitudinal air-current in the olland tunnels or in the Detroit-Windsor tunnel. On several casions he tested the matter when standing on the sidewalk of e tunnel, by blowing volumes of cigarette-smoke into the air; the oke ascended almost vertically to the air-grids in the ceiling mediately overhead. Even on a Sunday in August, 1931, when 27 vehicles came into New York through the south tunnel between dnight and 1 a.m., he noticed that there was hardly any longitudinal -current, as the cigarette-smoke ascended with only a very slight lination towards the direction of the traffic. In the Holland nnels, even at times of maximum density of traffic, the carbon-noxide content rarely exceeded 2 parts per 10,000, and a complete ange of air in the tunnel took place forty-two times in 1 hour, or ce in about 1½ minute. He had checked that figure by examining carbon-monoxide records for a considerable period, and had ken particular note of the results for Sunday nights, when the ffic was most intense, but he had found no record as high as parts per 10,000. He was told that there had been one or two ords slightly in excess of 2, but those were far short of 2·5, although ventilation-arrangements were designed on the basis of 4 parts 10,000. It should be noted that all the American vehicular aqueous tunnels, as well as the Antwerp tunnel, were ventilated the upward transverse system.

t might be of interest to record a few facts about those tunnels l also about other American vehicular tunnels, particularly in ard to the differences between them and the Mersey tunnel. e traffic in the Holland tunnels in the year 1931 amounted to 756,174 vehicles, as compared with 3,063,923 in the Mersey nnel during its first year. On one Sunday in 1931, 59,000 vehicles sed through the Holland tunnels in 24 hours, and the maximum ffic in one tunnel for one hour in one direction only had been over 00 vehicles. The traffic figures on Sundays normally exceeded

Mr. Gedye. 50,000, and on the particular day on which he spent some ho there, he believed the figure was 52,000. The official estimate of maximum traffic-capacity of the Mersey tunnel was, he believ 4,150 vehicles per hour with four lines of cars spaced 100 feet ap and moving at 20 miles per hour. It did not seem possible, howev that such a figure could be realized in practice in the Mersey tunn even supposing that the in-going and out-going streams were eq in volume, because of the inevitable check caused by the crossing traffic lines at the junctions of the branch tunnels with the m tunnel in Liverpool and Birkenhead. It seemed to him that arrangement of the branch-tunnel traffic crossing the main-l traffic in the Mersey tunnel was in many ways an undesirable featu and must result in considerably reducing the traffic-capacity of main 4-way tunnel, unless at times of intense traffic the branches w temporarily closed; in that case it would be possible to get nea 4,000 vehicles passing through the main tunnel alone if the nor and south-going streams were approximately equal in volume.

All the subaqueous vehicular tunnels at present in operation the United States, with the exception of the Holland tunnels, w single tunnels providing for two lines of traffic in opposite directio In the Detroit tunnel, in spite of international customs and passp regulations at both ends, a traffic of more than 2,000 vehicles hour on two lines of traffic in a single tube was reached even in period of intense industrial depression which followed its opening 1930. The maximum daily intensity of traffic up to 1931 10,800 vehicles, but that figure was much below the maxim capacity. In the Oakland tunnel, under an arm of San Franci Bay, the number of vehicles passing through the single two-w tunnel had exceeded 1,800 in each direction per hour; that w 3,600 for both directions. The Sunday and holiday traffic var from 22,000 to 27,000 vehicles, and the weekday traffic from 18, to 20,000 vehicles, per day. The tunnel under Boston harbour also a single two-way tunnel.

It need not be assumed that the difficulty of clearing traffic-blo due to accidents was greater in a small two-way tunnel than i four-way tunnel such as that under the Mersey. He had witnes a collision in the Holland south tunnel on the Sunday night summer to which he had already referred, the particulars be noted by the Chief of Police, who was with him, and himself. T happened to be standing on the footway close to the site of occurrence. The east-going traffic at that moment—he looked at record afterwards as a check—was at the rate of about 2,500 vehi per hour in the one tunnel. Two cars, going in the same directi became locked. The traffic was at once cleared in advance of

Mr. Gedye.

ked cars, and was resumed in one lane in 2 minutes after the cident. The breakdown-car came into the tunnel, but it was not quired, as the cars were separated in 3 minutes from zero time and re able to proceed under their own power, although both were maged. Traffic in both lanes was proceeding normally in under minutes from the time of the impact.

There was another point of difference to which he might draw tention. The cross-sectional area of the Mersey 4-way tunnel s 1,680 square feet, while that of each of the 29½-foot diameter olland tunnels was 683·4 square feet. It seemed to him that if a gle 2-way tunnel had been constructed under the Mersey in the st instance, it might have been available for traffic several years fore the present tunnel was available, and would have been amply ficient for all the traffic which at present used the tunnel. The nnel might have been duplicated if and when the growth of traffic tified such duplication. An enormous saving in initial cost uld have been made and a consequent saving on interest and ortization charges for a good many years. The cost of two 2-way nnels under the Mersey would, he suggested, have been less than cost incurred in building the Mersey tunnel in its present form, l incidentally the traffic difficulty to which he had referred would ve been obviated in that way. The so-called "Mid-Town" nnels, which represented the most recent American practice, and first of which was now being driven under the Hudson higher the river than the Holland tunnels, would be twin tunnels, each feet in external diameter. In the first instance the south tunnel, ich it was expected to open for traffic early in 1938, would be ized for two-way traffic with one line in each direction, as in all other American tunnels except the Holland. At some later e, when the growth of traffic justified its construction, the second nel would be built, and, when both tunnels were in operation, would be used for two lines of east-going traffic and the other two lines of west-going traffic, as in the Holland tunnels.

n the ventilation-plant of the Holland tunnels, the motors and s were of much smaller individual capacity than those in the sey plant, but there were eighty-four fans in all, as compared h thirty in the Liverpool and Birkenhead buildings. One-third hose fans comprised a reserve of 50 per cent. over the normal imum output of 3,760,000 cubic feet of fresh air per minute, ch was the capacity of the blowers alone, excluding the reserves. the fans were driven by 5-speed motors, and at times when the fic was relatively light, one set of two fans, one blowing and one austing, in each of the fourteen ventilating-sections, sufficed to ntain sufficient ventilation when run at the lowest speed. It

Mr. Gedye. had been established that samples of air taken in the open near t junction of 42nd Street and 5th Avenue in New York frequen contained a higher proportion of carbon monoxide than was ev met with in the tunnel. His own view was that upward transve ventilation, as in the American tunnels, was the system to be p ferred in tunnels of relatively small diameter carrying two lines traffic, although there were probably distinct advantages attachi to the semi-transverse system in the case of tunnels of very la diameter, such as that under the Mersey.

The paving used in all the American tunnels was granite set In the Holland tunnels the setts were in straight lines transverse The granite paving in the Detroit-Windsor tunnel was, howev laid in courses of circular arcs and the joints were run in with l bitumen and sand. The surface was said to be very satisfactory a much better than that of the Holland tunnels. It was claimed tl skidding had been practically eliminated by the paving in t Detroit tunnel, and he believed that a similar paving had been used the Boston tunnel.

Mr. Kennedy. Mr. J. J. S. Kennedy said that the Paper was of especial inter to him, as it described much of which he had been ignorant during connection with the Mersey tunnel, which dated from January, 19 He would like to ask one or two questions on matters other than actual construction and structure of the tunnel. Would the Autl tell him the air-velocity in the north and south air-ducts? would also like to know the velocity along the south air-duct h way from the Liverpool bank to the neutral point where the Liv pool air met the Birkenhead air. It had been stated in 1931 that velocity would be about 40 miles per hour, and there was so alarm at the prospect of having to make high-voltage cable-joints such a high horizontal wind. In the section on ventilation Author stated that the inlet-velocity to any section was never than 15 feet per second with the full quantity of air passing. T gave a speed of about 10 miles per hour, but in *Figs. 9*, the cu showed a maximum flow near the entry equivalent to about 19 m per hour.

In the section of the Paper headed "Control-Room" (p. 507), Author mentioned the diminution of visibility owing to smoke fog. Visibility might be diminished by either solids in the air, smo dust or dirty fog, which obstructed actinic light, or by clean conden water-vapour, such as mist, which merely diffused the light. problem was analogous to that of working the lighting of aerodro automatically by the diminution of visibility when there had b no diminution of actual light. He would like to ask whether far, any clean mist had been experienced in the Mersey tun

ether the light-sensitive cell functioned equally well with clean Mr. Kennedy.
st, and whether it was intended to make the photo-electric cell t only indicate the visibility but also actuate the tunnel lighting. was satisfactory to learn that light-sensitive apparatus was being ed for vehicle-counting and for vehicle-height limitation.

He would also like to know why air-flow recorders of the impact-te type were being used, and whether consistent and true readings re possible with such recorders. In the section on ventilation the ot-tube type was stated to have given the only reliable results, l that confirmed his own experience in aviation work and in large wer-station flues and chimneys, which was that a small Pitot d, with its static and dynamic orifices connected by its concentric e to a manometer, was the only reliable means of finding the ocity and direction of air-movement. He had found that no plate with sharp edges could give true results, as it involved bulence and itself interfered with the air-flow. He had watched ecorder of that type in the main air-duct under George's Dock the vious summer.

The Mersey tunnel was thought of primarily as a road-traffic te between Liverpool and Birkenhead, but it was also the main wer-connection route between those two cities, with a carrying-acity of 40,000 kilovolt-amperes at a potential of 33,000 volts. The le-run presented unusual features, of which there had been no vious experience. He had been responsible for the design of t cable-run, for the preliminary prospecting, for the specification l contract, and for the supervision during construction. It was n recognized that the cable-run involved major engineering rations and problems. Although the cable-contract was not de until July, 1932, prospecting visits had had to be made during latter part of the construction of the tunnel in 1931, before the k excavation was finished or any of the roadway made.

The cable-run in the tunnel was briefly as follows. It ran down m Brunswick street (Figs. 1, Plate 1) at George's Dock, ough a hole which was bored through one of the arches of a duct, through a cable-subway 6 feet by 6 feet by 70 feet in rein-ced concrete which had to be made under the future tunnel-kshops, and down to the tunnel by a vertical shaft and passages. continued (Figs. 1, Plate 1) through the circular part of the nel under the Mersey by the south air-duct, and then up peth Dock working-shaft to become again ordinary underground le in Shore road, Birkenhead. The cable-cores were each of 5 square inch in area, the cable used being of the 33-kilovolt re Hochstadter sheathed-lead type, bare-wire-armoured and erproofed where it lay in the ground. It weighed 56·1 pounds

Mr. Kennedy. per yard, and had an outside diameter of 3·88 inches with a minim bending radius of 6 feet. Three of those power-cables, together w one pilot-cable, had been run through the tunnel, and space b been arranged throughout, with ducts and hook-racks, to acco modate another three cables and pilot-cable, making a total fut capacity of approximately 80,000 kilovolt-amperes.

Some points in the design of the run which had had to be de with might be mentioned. The joints in the south air-duct h to be of special design and staggered in order to avoid any obstructi to the air-flow. On vertical runs the cables were gripped by te grips 2 feet in length spaced vertically 10 feet apart. Informati from South Africa and elsewhere was obtained, so as to avoid r of too high a clamping-pressure damaging the cable, or of too low pressure allowing it to slip. Previous experience was not availa to deal with the gradients involved by the cable-run or with vertical 33-kilovolt cable, and the problem of oil-migration at joints had to be considered. The arrangement of the different ty of joints was that there were two barrier reservoir-joints at the and bottom of each vertical run, and one ordinary barrier joint alo the tunnel at a lower position. High-voltage cables for 33,000 vo had to be handled carefully, and the difficulty of getting them i place in the run through the tunnel would be appreciated.

Mr. Lister. Mr. J. E. Lister, after congratulating the Author on an excell Paper, remarked that he had been directly concerned only with ventilation-problem, but had spent a great deal of time in the tun during the whole of the construction period. The Author referred to Mr. Lister's visit to the United States with the late Hewett. He had been very pleased to have the opportunity making that visit and of seeing what had been done there in ventilation of vehicular tunnels. At that time there were o two such tunnels actually in use, the Holland tunnels and Pittsburg Liberty tunnels, but Mr. Hewett and himself had a seen the Detroit-Windsor tunnel, which was then under constructi Unfortunately, time had not permitted them to go to San Franci to see the Oakland tunnel. He would like to express his thanks he was sure Mr. Hewett would have wished to have done, to Singstad and the other American engineers, who went to a great d of trouble to see that the visitors had every opportunity of inspect both the work in and on the tunnels and also the ventilation-buildi

As the Author had mentioned, the New York and Pittsb tunnels, which were the only ones then open, were designed single-way traffic, and the problem of ventilation was quite differ from that in the Mersey tunnel, with its larger area and bra tunnels. As a previous speaker had remarked, owing to that

he individual fans used in America were very much smaller than Mr. Lister.
ny which had been installed for the Mersey tunnel. As the Author
as aware, he had particularly noticed the use of two fans in parallel
or the peak loads, and he had advocated that, and would still
dvocate it, for any medium-sized installations. In the case of the
Iersey tunnel, however, a single fan dealt with the whole of the air
ı each section, except in the case of the fresh-air fans at Woodside,
here constructional difficulties had made it necessary to run
eparate supply shafts down each side of the tunnel.

Owing to those features, the largest fresh-air fans in the Holland
unnel—the conditions in which were somewhat comparable with
hose of the Mersey tunnel although, as Mr. Gedye had pointed out,
handled a great deal more traffic at present than the Mersey tunnel
–were designed for a volume of 218,000 cubic feet per minute, as
gainst 496,000 cubic feet per minute in the case of the George's
ock fans. The largest exhaust-fans in New York were designed to
andle only 227,000 cubic feet per minute, as against the 641,000
ubic feet per minute of the exhaust-fans at Woodside.

The Author had mentioned the difficulty of estimating exactly
hat the resistance of the various sections of the ventilation-system
ould be. Although there was nothing strictly comparable with
ıe conditions at Liverpool (owing to the larger size of the Mersey
ınnel and to the different dimensions of the ducts, as well as to the
resence in them of columns supporting the roadway), he had studied
ll the information available from various sources at that time; he
ad arrived at certain figures for what he thought was likely to be
ıe resistance of the various sections of the tunnel, and had allowed
small margin for safety. Owing, however, to the care with which
ıe surfaces of the ducts were finished and to the streamlining of
ostructions, and in spite of the cables put in by the previous speaker,
ıe actual resistance was, in most cases, appreciably less than the
timated figures, and consequently the actual volumes delivered
y the various fans when running at full speed were greater than the
gures originally calculated. He agreed with the Author as to the
applicability of the Singstad formula to the conditions of the Mersey
ınnel, but it did give a fair indication of the approximate values of
ıe resistances of the various ducts before a sufficient length of the
ınnel was completed to allow the full-scale tests to be conducted.

The regain of pressure-head due to the conversion of velocity-head
the air-stream into pressure-head at the end of a long duct, where
r was taken off more or less uniformly along the whole length, was
own in *Figs.* 9 of the Paper. That result agreed with what would
expected in theory, and similar results were obtained during the
sts in the experimental length, where the slot openings were made

Mr. Lister.

adjustable for purposes of experiment. Those slots, set in accordanc with calculations, gave almost uniform flow throughout the whol 1000 feet tested. There were measuring-stations in the duct ever 100 feet, and readings were taken which showed an almost equa increment at each station. Some doubt had been expressed durin the earlier discussions on the problem of the Mersey tunnel, as t the effect of foggy weather on the atmosphere in the tunnel, but h believed that, as he had anticipated would be the case, the atmospher in the tunnel during such foggy periods was considerably bette than outside, and that no traffic-delays had been caused in the tunne by fog.

Mr. Gedye had mentioned that, when he visited the Hollan tunnel in 1931, there was no longitudinal air-flow along the tunne When Mr. Lister and Mr. Hewett visited that tunnel, in Novembe and December, 1929, there appeared to be a definite flow alon the tunnel, and the engineer gave them a figure of approximatel 10 miles per hour. A similar figure was obtained in the tunnels a Pittsburg, which were through a hill, and advantage had been take of it in that case to use a longitudinal system of ventilation. Bot the blowing and exhaust fans were placed near the centre of th tunnel, and there were separate tunnels for traffic in each directio each single-way. The exhaust fan drew from one portal to th centre of the tunnel, and the blowing fan delivered fresh air at th centre towards the other portal, in the direction of the traffic-flo The only trouble experienced with that system was that und certain conditions of head-wind the path of the ventilation-air wa blocked by the opposing wind. A false portal was therefore built few yards away from the true portal, and the space between acted a form of chimney, up which the two opposing air-currents we able to flow.

Mr. Colquhoun had mentioned that the fans installed were of th centrifugal type, " which had been in use for the last hundred years and had stated that the axial-flow or propeller-type fan had no reached a state of development when it demanded consideratio Mr. Colquhoun appeared to overlook the fact that improvements the design of centrifugal fans had also taken place in recent yea which had resulted in a great improvement in their efficiency. I agreed that the axial-flow fan had been greatly improved recentl and that for certain purposes it was admirable, but the improveme effected up to the present had not succeeded in overcoming t trouble of noise, which he believed had been the main reason for n adopting those fans in the case of the Mersey tunnel. As compar with centrifugal fans, the amount of noise produced was very mu greater. That could be understood from the fact that for equ

ressures the peripheral speed of a propeller-type fan must be very nuch greater than that of a centrifugal fan, and the amount of oise increased very rapidly with increase of speed. He had ecently seen three or four axial-flow fans of the latest design, but ney were much more noisy than centrifugal fans of equal capacity nd working against equal pressure would have been. The maximum ntensity of noise, which was given as 80 decibels in the Paper, was egistered for a fan running at a much higher speed than was actually equired in the case of the fans which had been installed. The experi-nents were arranged before the decision was made to omit the upper r ceiling duct; at that time it was thought that it might be necessary) have a ceiling duct, in which case a much higher water-gauge reading ould have been required. At that time, moreover, it was thought nat 300 cubic feet of air per foot-run of tunnel, instead of 200 cubic eet, might be necessary. With regard to the question of reliability, e did not think that that need be considered, because there should e no great difficulty in designing an axial-flow fan to run satisfactorily or many years. He would like to mention that the modern type of entrifugal fan, as exemplified in the fans which he had had the honour f designing for some of the installations, was for equal capacity nly about half the diameter of the old type of mine-fan men-oned by Mr. Colquhoun. In addition, the centrifugal fan had a self-miting power-characteristic, which was of considerable importance n cases where, as in the Mersey tunnel, there was some doubt as to ne actual resistance of the completed system, as it ensured that under o conditions could there be serious overloading of the driving motor) long as the speed did not exceed the specified figure. Mr. Lister.

Mr. Colquhoun had also referred to the size of the buildings ecessary to house the fans. It was necessary to remember that in ne larger buildings accommodation was provided for transformers nd other equipment, and the buildings were considerably larger nan was actually necessary for the fans themselves.

He had been interested in the carbon-monoxide figures given by Ir. Colquhoun, because he had always been under the impression nat British engines would not be quite so liberal with their emission f poisonous gases as American cars had been shown to be in the merican tests. Those figures were the results of tests on more than hundred vehicles of various types and sizes, and covered tests on ırs standing with engines idling and racing, and at speeds up to 5 miles per hour on the level, up and down gradients, and both light nd loaded. The figures were summarized in Table III (p. 540).

From those figures it would be seen that the average emission or those American vehicles was approximately 0·6 cubic foot per inute with engines idling, and $1\frac{1}{2}$ cubic foot per minute under

Mr. Lister.

all conditions, with a maximum, when pulling fully loaded up 3 per cent. gradient, of 2·7 cubic feet per minute for all vehicles. Generally speaking, a car emitted from two to three times th

TABLE III.—CUBIC FEET OF CARBON MONOXIDE PER CAR PER HOUR.

Type of vehicle.	Mean of light and full load.			Full load only.		
	Minimum.	Maximum.	Average.	Minimum.	Maximum.	Averag
5-passenger car . . .	29	77	52	—	—	—
7 ,, ,, . . .	42	144	89	39	164	98
Truck up to $1\frac{1}{2}$ ton . . .	31	96	61	37	118	67
,, , $1\frac{1}{2}$–3 tons . . .	15	135	80	24	150	91
,, , $3\frac{1}{2}$–$4\frac{1}{2}$,, . . .	55	184	119	50	182	113
,, , 5 tons and over . .	51	182	111	48	199	129
Average	37	136	85	40	162	100

volume of carbon monoxide when going up a gradient than whe running downhill, while on the level the figure was approximatel a mean between those figures.

Typical analyses of the exhaust gases were as follows :—

	On level.	Up 3-per-cent. grade.
Carbon dioxide	8·9 per cent.	9·6 per cent.
Oxygen	2·3 ,,	1·3 ,,
Carbon monoxide	6·3 ,,	6·4 ,,
Hydrogen	3·0 ,,	2·9 ,,
Methane	0·9 ,,	0·6 ,,
Nitrogen	78·6 ,,	79·2 ,,
	100·0	100·0

Actually, the figures given by Mr. Colquhoun agreed fairly we with the American figures for the lighter class of vehicle. Th Americans had taken $1\frac{1}{2}$ cubic foot per minute as the average for a the vehicles tested, and the ratio of heavy lorries to light ca appeared to have been almost exactly the reverse of what had bee observed in the case of the Mersey tunnel. The whole subject c tunnel-ventilation was one of very great interest and importance, i view of the recent and probable future development of motor traffi and it would remain so until an internal-combustion engine wa produced which did not emit carbon monoxide.

Mr. Lister then showed some lantern-slides of the fans installed i connection with the Mersey tunnel.

Mr. Williamson.

Mr. JAMES WILLIAMSON joined with previous speakers in co gratulating the Author on his Paper, and said that he had bee particularly interested in some of the details given with regard to th actual tunnelling, as the headings were comparable in size wit some of the tunnelling-work on the Galloway water-power schem

The 11-foot 6-inch Glen Lee tunnel, which was completely lined with concrete, was about the same size as some of the headings described in the Paper. The rock was harder than the sandstone with which the Author had to deal, and would not blow so cleanly, whilst the charges had to be about $3\frac{1}{2}$ lbs. of dynamite per cubic yard, as compared with the figure of under $1\frac{1}{2}$ lb. given by the Author. One of the reasons, no doubt, why those large charges had been introduced was because speed was necessary, and the rate of driving ahead in that particular tunnel was, on an average over a good period, 100 feet per week. In a more recent tunnel of smaller size, where driving in rock began at the end of 1934 and was completed at the end of 1935, a length of 6,000 feet was driven from one end in a period of roughly 50 weeks, the average rate being 120 feet per week. The maximum weekly rate was something over 140 feet, or 1 foot progress for every working-hour. Those water-tunnels were very small compared with that which the Author had described, but there was also a short length of tunnel of a larger size, 22 feet in width by 18 feet in height, to carry water through under pressure. The rock was considerably jointed, and the whole of the rock at the back of the concrete lining was grouted. Mr. Williamson.

The cost of that tunnel worked out at just under £30 per linear foot, and it was estimated that the completely-lined rock-tunnels would cost, for the smaller sizes, about £1 per linear foot for each foot of diameter. For the larger sizes the cost would be greater; in the case of the 22-foot tunnel to which he had referred, the cost per linear foot would be about $£1\frac{1}{3}$ for each foot of diameter. That tunnel was nearly large enough to take two lines of traffic, and he had made a rough calculation that in similar circumstances, with a completely-lined concrete tunnel big enough for two lines of traffic, the cost would work out at from £50 to £60 per foot. Those conditions were widely different from the conditions with which the Author had had to deal under the river Mersey, where there was a high pressure of water to deal with; it had, however, occurred to him that, as had already been suggested, even if a cast-iron lining had to be used, two tunnels each arranged for two lines of traffic would probably have worked out more cheaply. If compressed air had been required he thought they would certainly have been more favourable from the point of view of construction, as the bottom of the tunnels could probably have been some 18 feet higher than the bottom of the larger tunnel.

Mr. T. H. Webster remarked that he would like to ask one or two questions on matters which might have puzzled others besides himself. With regard to the cast-iron lining, the Author had said that the top half was put in first. He could not understand how the Mr. Webster.

Mr. Webster. lower half was then put in without the top half falling down a certai amount.

There were fourteen different headings or "break-ups" and a cast iron lining was put in each heading. Unless that lining were ver accurately started in each one of those headings, trouble would aris when the cast-iron linings in the headings met, and it would be c interest to know with what degree of accuracy those headings met When fourteen headings met in thirteen different places there woul be thirteen joints, and he wondered whether any trouble had arise in connection with the axes not being coincident in all those cases.

The Author. The AUTHOR, in reply, said that a question which had been raise by several speakers was why one tunnel of large diameter had bee adopted instead of two tunnels of smaller diameter. There were number of reasons for that, one being that it was desired to have broad thoroughfare, like Dale street, joining the two towns. Fron a spectacular point of view, and certainly from the point of view c general airiness and flexibility of traffic under exceptional conditions one large tunnel carrying four lines of traffic, provided that it was no too expensive, was to be aimed at rather than two separate tunnel each with two lines of traffic. If the tunnelling had had to be don through bad ground or soft ground, he admitted that it would hav been necessary to adopt separate tunnels, but the tunnelling wa done through continuous sandstone-rock, which lent itself readil to large-scale excavation. Another point to be borne in mind wa that, in fact, accommodation for six lines of traffic had been provided there were four lines of traffic on the horizontal diameter, and ther was room for two more lines of traffic in the space underneath which was 21 feet in width and about 17 feet in height. It would therefore, have required three separate tunnels, each with two line of traffic, to afford a fair comparison with the one large tunnel whic had been constructed.

A problem which, however, arose was that of the branch tunnel It was a feasible engineering proposition to take a small branc tunnel out of a large main tunnel, but considerable difficulties woul be found if an attempt were made to take a branch tunnel out c another tunnel of the same size. That led him to the statemen which had been made to the effect that there was an interruption c traffic where the branch tunnel diverged from the main tunne That was true, and fly-under and fly-over junctions had been con sidered; but, with one gradient seeking to connect with anothe gradient it became an extremely difficult piece of work, and, whi either would have given more uninterrupted running, it was foun necessary to adopt the junction chambers that were ultimatel constructed.

There was another point to which he would like to refer: namely, the capacity of the tunnel. The tunnel, so far as ventilation was concerned, had been designed on the basis of a dilution of 2·5 parts of carbon monoxide per 10,000 parts of air, and on the assumption that 12,000,000 vehicles per annum would ultimately use the tunnel. At the moment, only about 3,000,000 vehicles were using it, and the carbon monoxide, with the fans only running at half-speed, was about 1 part in 10,000 at present. The 4 parts in 10,000 to which Dr. Lowe-Brown had referred could occur only in a time of panic. If there happened to be a panic, and vehicles were left in the tunnel with the engines running, it might be possible for the dilution to reach 4 parts in 10,000; but even under those almost absurd conditions—but conditions which, nevertheless, had occurred in the Pittsburg tunnel—the ventilation plant would keep the dilution at 4 parts per 10,000, and it would still be safe to go into the tunnel and to shut off the engines. The Author.

Mr. Peirson Frank was quite right in drawing attention to the fact that the tunnel as actually built was considerably longer than that in the design originally placed before Parliament. The additional length was one of the reasons why the cost had been greater than the original estimate.

With regard to the section of rubber-surfaced roadway, it was situated on a bend, and not far from the open portal; some skidding did take place, due partly to the wheels of cars bringing water in with them and so wetting the surface, and also because strangers to the tunnel were apt to apply the brakes of their vehicles somewhat suddenly when they saw a change in the surface from the cast-iron paving.

In connection with the cementation-process, pressures of about 200 pounds per square inch were used at first, but were found to be too high, as the cement got into the horizontal layers, and tended to lift the immediate neighbourhood. Pressures were then reduced, so as to balance the hydrostatic head of the water in the rock.

The whole credit for the introduction of the suspended roadway lay with the contractors, and he doubted whether the progress that had been made could have been achieved without it.

The figures given in Table II by Mr. Colquhoun were of very great interest, as they showed that, in spite of all the difficulties that had been encountered, the Mersey tunnel compared very favourably in cost with other tunnels. The Author agreed with the reference to propeller-type fans, and he thought that such fans had now reached such a stage of development that they would have to be very seriously considered in connection with future tunnels, and that considerable economies would result from their adoption. Unfortunately, when a decision had to be made regarding the fans for the Mersey tunnel,

The Author. the propeller-type fan had not been sufficiently developed to justif its adoption.

The remarks regarding the use of structural steel and concrete i place of cast iron for the lining of the tunnel were very interestin The Paper showed that, above the water-table, rolled-steel joists an concrete had been used, and quite considerable economies had bee effected. In the under-river portion, where the water-pressure wa of the order of 80 pounds per square inch, the engineers had decide that cast iron must be adhered to, not only because of its practicall everlasting qualities, but because it could be made absolutely wate tight. The whole question of an alternative to cast iron was unde very careful consideration by the engineers as regards other tunnel and, in particular, in connection with the tube-railways of Londo

The Author was very anxious to try out reinforced-concrete an steel linings, but the questions of durability, ease of erection and eas of attaching fittings to the lining all had to be borne in mind.

As regards the thickness of 1½ inch for the skin, that was more c a problem of casting than one of strength; the thickness of 1½ inc was judged to bear a proper ratio to the thick and deep flanges, and t eliminate the cooling stresses as much as possible.

In order to keep the length of the Paper within reasonable limit a great many details had perforce been omitted, and the Autho would gladly consider the suggestion put forward by Dr. Lowe-Brow that further Papers might be submitted to The Institution b members of his staff and others connected with the work.

⁂ The Correspondence on the above Paper will be publishe later; the Author, in his reply thereto, will deal further with certai points raised in the Discussion.—Sec. Inst. C.E.

ORDINARY MEETING.

16 March, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The discussion on the Paper by Mr. Anderson on the Mersey tunn was continued and concluded.

ORDINARY MEETING.

17 March, 1936.

Mr. JOHN DUNCAN WATSON, President, in the Chair.

The following Paper was submitted for discussion, and the thanks of The Institution were accorded to the Author.

"Some Major Problems in the Utilization of Coal."

By Frank Sturdy Sinnatt, C.B., M.B.E., D.Sc.

TABLE OF CONTENTS.

During the past few years the elimination of wasteful methods in the utilization of coal has become the pressing concern of nearly every branch of industry. In certain processes the thermal efficiency attained is so high that major improvements are difficult to foresee, but this does not mean that great changes may not be expected in plant design. Coal burnt in the consumers' own plant is still the main source of power in this country, but coal gas and electricity, as they fall in price, will tend to take its place, particularly where industry or population is concentrated.

Among the factors of importance in the economical utilization of coal are :—

(*a*) The selection of the right coal for the purpose in view.

(*b*) Its preparation by cleaning and sizing into convenient grades.

(*c*) The design of the plant.

In connection with these factors the object of the present Paper is to draw attention to :—

(1) The Fuel Research Coal Survey, which is obtaining information of the properties of the seams in all the main coalfields.

(2) The recent developments in the preparation of coal for th market and in processes for the cleaning of fine coal, an particularly the work being done on the breaking an sizing of coal.

(3) The developments in the burning of coal in pulverized form

(4) The technique for the transformation of tar and coal int motor-spirit by hydrogenation.

The annual consumption of coal for domestic and general manufacturing purposes in Great Britain is about 100 million tons, treate in relatively small units. Although a plant may be highly efficien with coal of suitable characteristics, use of the wrong fuel may caus great losses. One of the difficulties experienced by producers an consumers arises from the diversity of the seams in the Britis coalfields. The coals on the whole are extremely pure, but the not only vary in properties from seam to seam, but frequently fron place to place in the same seam.

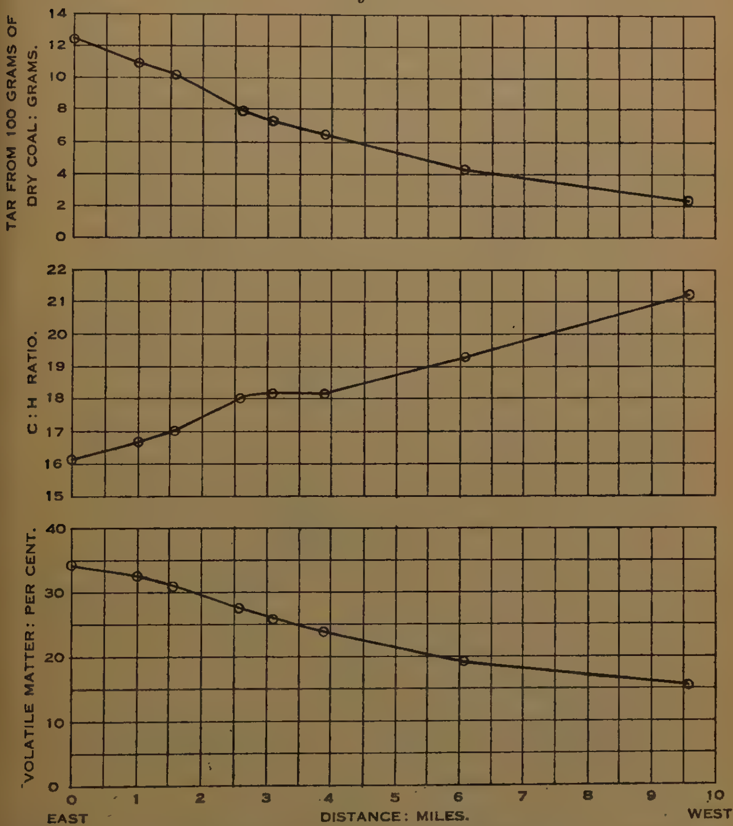
The Survey is actively engaged in all the coalfields of Great Britain and the characteristics of the different seams are published in separat reports. These are based on a physical and chemical examination carried out in one of the nine survey laboratories, of pillar section cut from roof to floor of the coal face. When necessary, this wor is supplemented by tests on a large scale in the plant at the Fu Research Station.

The results show the wide variations in properties that may occu For example, although the changes in character of the coals in th South Wales coalfield, from bituminous in the east to anthracite i the west, are well known, it is perhaps not generally recognized ho rapid the local variations are in some areas, and how uniform th coal is in others. *Figs. 1* give the analyses of eight samples of th Nine Feet seam, obtained within a distance of 10 miles. In th short distance the whole character of the seam changes and, passin from east to west, the volatile matter falls from 34 per cent. to ju over 15 per cent., the ratio of carbon to hydrogen rises from 16 to to over 21 to 1, and the yield of tar by low-temperature carbonizatio falls from $12\frac{1}{2}$ per cent. to $2\frac{1}{2}$ per cent. When such rapid chang in composition occur, co-ordinated information is essential to th collieries if they are to market coal of uniform quality.

The survey of a coal seam is not complete until the variatio have been presented in a precise form by plotting the points whe the characteristics have the same value. If such points are joine up on a map, lines of equal volatile matter content, for example, a obtained. One of the aims of the survey is to produce such a "isovol" map for all the coal seams, but great care must be exercis to ensure that no major alteration in the properties is overlooke

The survey of the Busty seam has just been finished and the isovol map is shown in *Fig. 2* (p. 548). The coal in this seam possesses outstanding caking properties and, together with others in the same coalfield, is the source of the excellent metallurgical coke produced in north-west Durham. As the seam is traced in a south-easterly direction its volatile matter content increases until on the other

Figs. 1.



VARIATION IN PROPERTIES OF COALS FROM NINE FEET SEAM, SOUTH WALES.

boundary it is used for gas-making. The isovol map may be used as an accurate guide to the way in which the coal varies from point to point in the coalfield, and therefore to determine the industrial use for which it is best suited in each district. It will be observed that in certain areas little change occurs in the seam, while in others rapid alterations take place in quite short distances.

The Parkgate seam of the South Yorkshire coalfield is remarkable

for the constancy of the values obtained by chemical analysis, and there are but small variations in the moisture, volatile matter and fixed carbon contents over a distance of 16 miles, as can be seen from *Fig. 3.* The South Yorkshire coalfield, however, extends into the Nottinghamshire and Derbyshire area, and here a seam called the

Fig. 2.

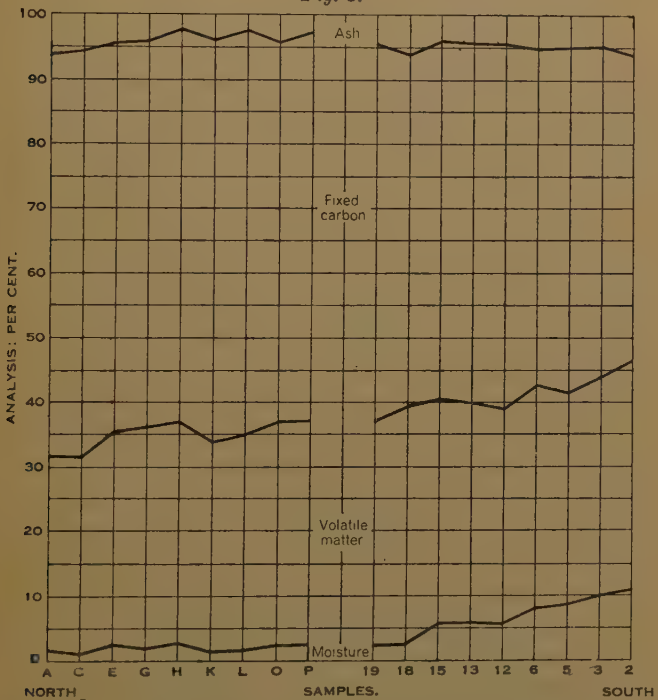
Isovol Map of the Busty Seam.

Deep Hard may be accepted as corresponding to the Parkgat although the correlation has not been quite definitely establishe As this seam is traced to the south, it shows rather striking chang in the contents of fixed carbon and of moisture, and the calorif value and caking power markedly decrease.

The survey of these two seams covers a distance of 50 miles fro north to south, and embraces some 2,000 million tons. Although the

change only slowly in chemical properties, they vary in thickness from 2 to 7 feet. They are characterized by a band of dull or hard coal with layers of bright coal above and below it. The variation in the percentage of dull coal over the field is shown in *Figs. 4* (p. 550). Although the dull and bright coals have similar chemical analyses, they are quite distinct in properties. The bright coal is highly caking and is used for the manufacture of coal gas and metallurgical coke, while the dull coal possesses only slight caking

Fig. 3.



PARKGATE SEAM. DEEP HARD SEAM.

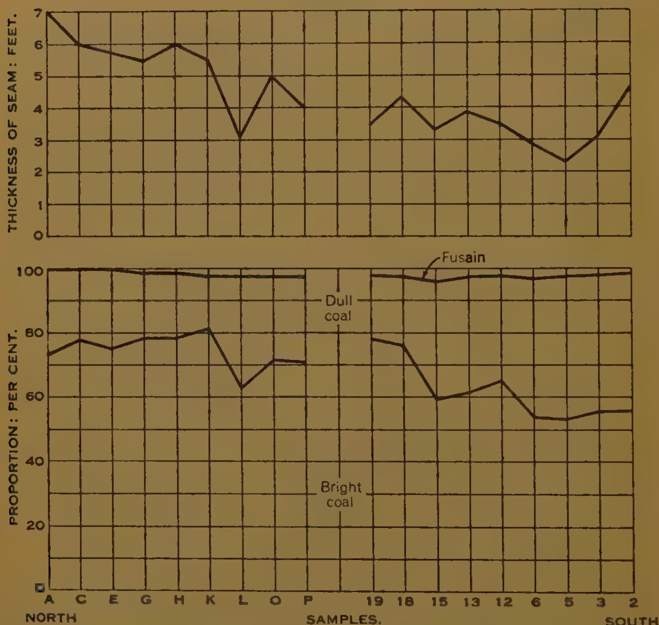
PROXIMATE ANALYSES OF SOUTH YORKSHIRE, NOTTINGHAM AND DERBY COAL.

properties, and is used as a locomotive coal and for general steam-raising. To meet these different markets the dull and bright coal are sorted out by hand-picking, but, generally speaking, it is not possible to separate them when the coal is small, although a process has been described in which the coal is fractured and the larger dull coal is screened off the smaller bright coal. The smaller sizes separated from run-of-mine coal are a mixture of bright and dull, so that their properties are governed by the proportion of the two

types present. It follows that coal of a similar size from different collieries may not have the same characteristics, although it is derived from the same seam. The difference in properties will not affect the efficiency of many plants, but may be important when the coal is used for carbonizing or, sometimes, for raising steam.

The situation is further complicated by the fact that collieries, as a rule, mine two or more seams at the same time. The natural corollary of a survey of coal in the seam is therefore an examination

Figs. 4.



PARKGATE SEAM. DEEP HARD SEAM.

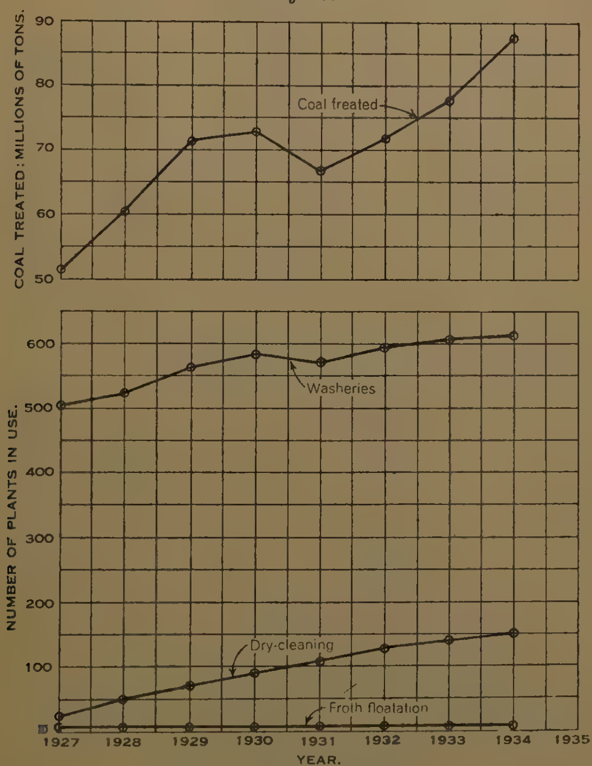
VARIATIONS IN SOUTH YORKSHIRE, NOTTINGHAM AND DERBY COAL.

of the commercial grades produced at the pit-head. This is being carried out in Lancashire and in South Yorkshire, and three reports on the subject have already been published. In South Yorkshire 360 commercial grades have been examined at 60 collieries, and taken in conjunction with the survey of the seams, provide accurate information of the properties of the whole of the output of this important field.

Closely associated with the Survey is the important question of the preparation of coal for the market. *Figs. 5* set forth graphically some of the statistics published by the Mines Department for the

years 1927–34. The upper graph shows the steady increase in the tonnage of coal that is mechanically cleaned before it is put on the market; in 1934, 87 million tons were so treated. This represents 40 per cent. of the total output, which, however, includes the large coal cleaned by hand-picking. Therefore, a fairer basis of estimation would be to exclude the larger sizes and to express the coal cleaned as a percentage of the output that is under 3 inches in size.

Figs. 5.



Coal-Cleaning Statistics.

It is understood that the extent of mechanical cleaning, calculated in this way, has risen to 80 per cent. in some of the fields.

Coal-cleaning plants have been in common use in Great Britain for over 40 years, but during the last 10 years enormous advances have been made in technique. The lower graph of *Figs. 5* shows the growth in the number of the different kinds of coal-cleaning plant. There are still four times as many wet-washeries as dry-cleaning installations in operation, but the latter are increasing rapidly in

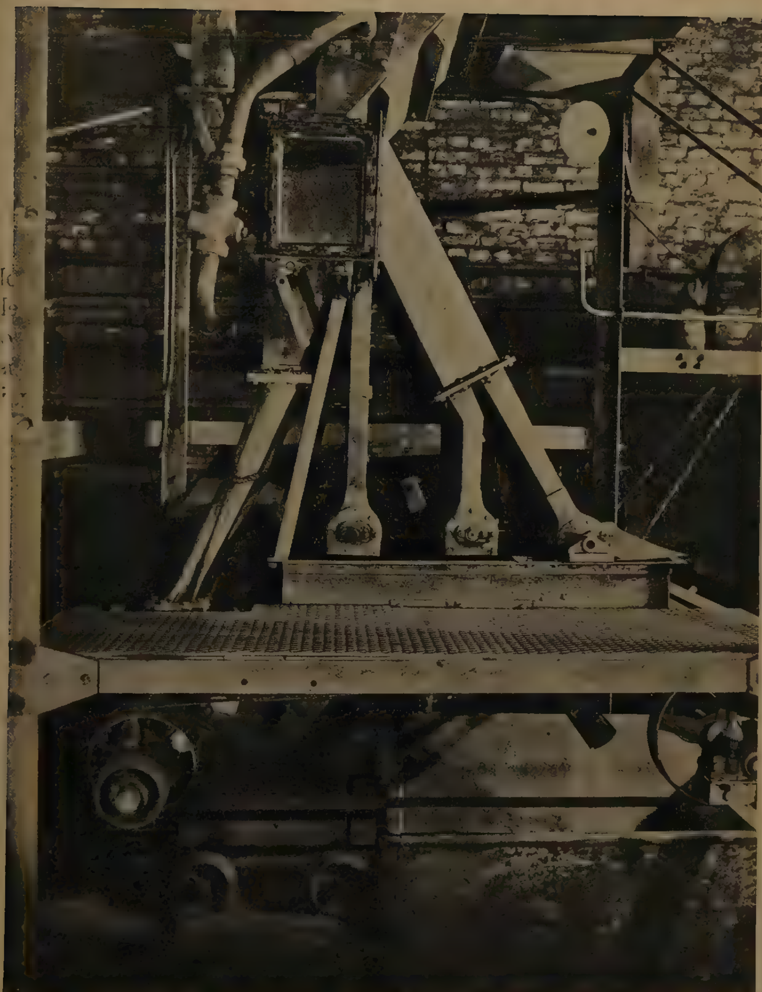
number. Recent improvements in washing plant have been mainly directed towards making the process fully automatic, but dry cleaning plant, relatively an innovation, has been very much improved.

The principles and mode of operation of the established cleaning plants are too well known to need description, but a new type of air-jig dry-cleaner is being developed at the Fuel Research Station. The first experimental model was designed by Dr. Slater of the South Yorkshire Survey Laboratory, and a large-scale unit, treating 30 cwts. of coal an hour, has now been erected at Greenwich.

The arrangement of the plant can be seen from *Fig. 6.* The coal is fed into the hopper above the plant, and passes down through the feed pipe into the back of the cell, which is 3 feet long and 1 foot wide near the bottom. Above the cell and extending its whole length is an air duct, to which suction and pressure are alternately supplied by bellows mounted immediately above. On the suction stroke, air is drawn through the coal causing it to loosen and rise slightly; on the pressure stroke, the air is forced downwards again and the bed is compressed on to the grid which forms the bottom of the cell. The repetition of the cycle causes coal and dirt to stratify, coal rising to the top and dirt falling to the bottom. The bed breaks on the suction stroke to leave a space into which fresh coal flows. Dirt is withdrawn through an off-take at the bottom, and clean coal flows from the top over a weir. A glass window is fitted to each end of the cell, so that its operation can be followed; the correct jigging action is obtained by adjustment of the speed and stroke of the bellows. The advantage of this plant is that it handles $\frac{1}{2}$-inch to 0 coal without any pre-screening or de-dusting. The power the machine uses is low and the problem of dust removal does not arise. The plant must still be considered to be in the experimental stage, but it already seems probable that it will fill a gap in the range of dry-cleaning equipment.

Under modern conditions of intensive machine mining, there is an increased production of fine material, which usually contains a higher proportion of impurities than the larger coal. If these can be separated, however, the fine coal can frequently be reduced to a lower ash content than the large coal. This is one of the most difficult problems facing the coal industry. The fine coal in question is obtained during screening and de-dusting, or as slurry from wet washeries. As a general rule the collieries try to dispose of as much of the impure dust and slurry as possible by mixing it with material rejected from the picking belts and burning it under the colliery boilers. Attempts are being made to use it, when dry, as pulverized fuel and, if inexpensive methods of removing grit from the flue gases

Fig. 6.



AIR-JIG COAL DRY-CLEANING PLANT.

can be introduced, some of the objections to this practice will be eliminated.

The cleaning of coal $\frac{1}{8}$-inch or $\frac{1}{16}$-inch in size and smaller is conveniently carried out by one of the two methods of froth-floatation. The separation is carried out in the first method at atmospheric pressure, and in the second under vacuum. As the former was described in detail recently by Dr. W. Cullen and Mr. H. Lavers,[1] it is only proposed to deal with the vacuum froth-floatation process. The place this method assumes in a complete scheme for the purification of coal has been described by Colonel K. C. Appleyard, of the Birtley Iron Company.[2]

An experimental plant capable of treating 2 to 3 tons an hour was erected at the Fuel Research Station in 1929, and many phases of the process have been investigated as applied to British coals. The fine coal is mixed with 5 to 6 times its weight of water and a small quantity of reagent. The most satisfactory reagents are fractions of petroleum, and the amount needed varies from 2 lbs. to $\frac{1}{4}$ lb. per ton of coal.

The suspension of coal in water is brought into a plant where it is placed under reduced pressure. A froth is formed that consists substantially of pure coal, whilst the shale and other impurities remain in suspension in the water and can be removed. When it is brought to atmospheric pressure, the froth collapses, and it has been found that the water drains from it more rapidly than from untreated coal. Many variations of the Elmore technique have been investigated at the Fuel Research Station, and it has been found advantageous in certain cases to separate the coal above $\frac{1}{16}$ inch in size, and to mix the reagent with the coarser particles, instead of adding it directly to the water and coal as a whole. Improved results were also obtained when the very fine material was removed by screening in the wet condition before treatment in the plant. To ascertain the characteristics of the coal in relation to floatation, a range of anthracites and bituminous coals has been examined in the plant. Floatability has been defined by the amount of oil required per ton to ensure a recovery of 96 to 98 per cent. of the pure coal. It was found that the quantity of oil required could be correlated with considerable accuracy with the percentage of carbon and oxygen in the coal. In *Fig. 7* (p. 554) it is seen that the decrease in floatability is relatively small until the percentage of carbon in the coal falls below 83 to 85 per cent., and thereafter it becomes rapid.

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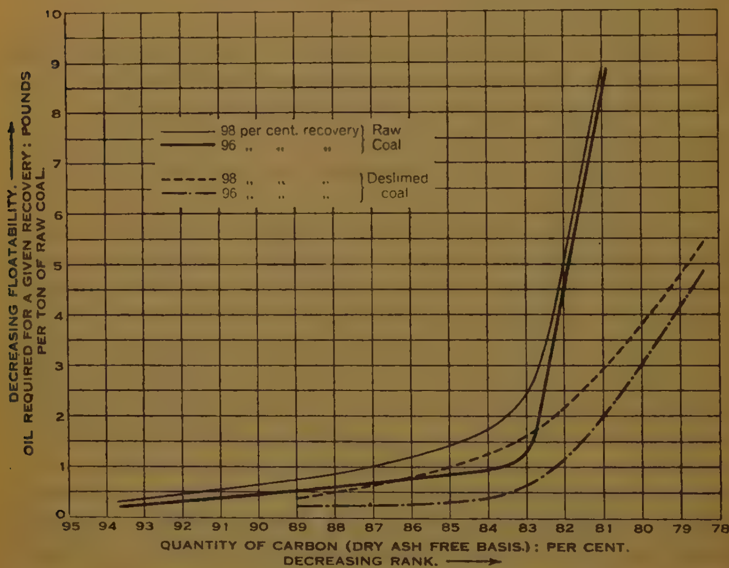
[1] "Flotation as Applied to the Chemical Industry," Trans. Inst. Chem. Eng., vol. 14 (1936). (15 Jan., 1936.)

[2] "The New Preparation Plant at the Rising Sun Colliery of the Wallsend and Hebburn Coal Co. Ltd.," Trans. Inst. Min. Eng., vol. xc. (1935), p. 37.

The two dotted curves in the figure emphasize the importance of removing fine material before treatment of low-rank coals.

In certain coalfields the demand for large coals, both for industrial and household purposes, is decreasing steadily. This has made the installation of coal-breaking machinery necessary and has turned attention to the conservation of graded sizes present in the run-of-mine coal. Graded coals are becoming increasingly valuable, and it is therefore necessary to study the breakage characteristics of coal and the coal breakers installed, to determine the most economical

Fig. 7.



Rank of Coal and Floatation-Properties.

manner in which the critical sizes can be produced. The consideration of degradation in size during handling and transport is equally important, as well as the effect of each of the treatments which coal has to undergo upon the sizes in relation to their commercial value. How many commercial undertakings are aware of the effect of handling and transport upon the potential output of graded sizes from the " face " where the coal is first won, and what proportion of those graded sizes ultimately reaches the consumer ?

An organized programme on this subject is in progress at the Fuel Research Station and in a number of the Coal Survey Laboratories. In one case it was discovered that the run-of-mine coal contained 13 per cent. of a size of particular commercial value at the mine,

but only 4 per cent. by the time it reached the consumer. In a second case, coal breakers were producing 30 to 35 per cent. of a particular size, whereas, when the coal had been transported to the central screening plant and had passed through it, only one-half the quantity of that particular size was available for sale.

The breakage of coal is in fact becoming of paramount importance and it raises problems which must arouse the interest of all engineers. The questions involved are most diverse and are concerned with mining technique, the handling of coal, the design of breakers, and the efficiency of cleaning and of screening. It is recognized that a number of firms are making rapid progress in meeting this new demand, but the problems involved are so intricate that detailed research is required into practically every aspect of the subject.

In the past it has been the practice to recover the coal from the mines as large as possible, and it is a matter for discussion whether this is not still the most economical procedure. The whole question is in the minds of the coal industry, as the recent Paper by Mr. H. E. Mitton and Dr. D. T. Davies shows.[1] It will be obvious that, if large coal is no longer required, it might be desirable to mine it in small sizes, in which case quite a new procedure would have to be adopted as regards coal-winning methods and choice of explosives.

An examination of the performance of certain coal-breaking machines has been carried out by the Fuel Research Organization in collaboration with certain collieries in South Wales, and this work was published in an Appendix to the last annual report of the Fuel Research Board. The work has been extended to an examination of the relative stability of the graded sizes produced from large coal by coal breakers. Consignments of nuts, produced by screening from the run-of-mine and by breaking surplus large coal, have been sent from the coalfield to the Fuel Research Station, where the degradation in size due to transport has been determined.

Size stability is not the only difference to be expected between these two products. It is most important to bear in mind that, even though produced from the same seam, they may vary considerably in properties and in their proper sphere of utilization. Incidentally, as breaker smalls are naturally relatively clean, they may, by further washery treatment, provide an ideal source of ultra-clean coal for hydrogenation or other coal-processing plants.

The question of the sizes in which coal is sold is already under examination in several of the coalfields. It seems to be generally recognized that a reduction in their number is desirable, as may

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[1] "The Grading and Classification of Coal," Trans. Inst. Min. Eng., vol. xc (1935), p. 3.

well be believed when in one coalfield over one hundred different grade-sizes of coal are produced by the collieries. Over a large part of the Continent eight sizes have been standardized, and this range is considered to be sufficient.

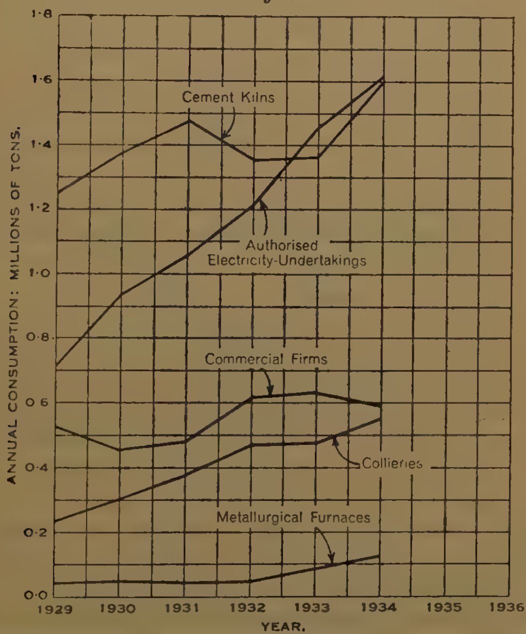
There are, however, two reasons why the rationalization that must take place should be carefully planned. First, the needs of the coal-burning appliances actually in operation must be considered. In this country they vary so widely that the reduction in the number of coal sizes, particularly below 1 inch, must be carried out cautiously. Second, although the development of automatic stoking and charging has increased the demand for accurately-sized coal, there is much that is not known of the influence of fuel size on combustion efficiency. In designing a stoker, for example, engineers to-day require it to burn fuel of a certain size; is this choice dictated by mechanical considerations or is it certain that the size chosen is the one best adapted for economical combustion in the furnace space? These questions have been examined for at least one size of coal, pulverized fuel, and it is largely as a result of such investigation that the efficiency with which it is used has increased so greatly in recent years.

In the returns published by the Mines Department, a steady rise in the consumption of pulverized fuel from $2\frac{3}{4}$ million tons in 1929 to $4\frac{1}{2}$ million tons in 1934 is shown. Although these figures represent only a small percentage of the total fuel-consumption of industry, analysis suggests that for specific purposes coal in pulverized form is well established. For example, pulverized-fuel firing is normal practice for cement kilns, so that the fluctuations in consumption (*Fig. 8*) reflect largely variations in the production of the industry. On the other hand this method of heating metallurgical furnaces is still advancing (*Fig. 8*), as its advantages in the control and maintenance of constant temperature, together with its economy, become more widely realized. The number of metallurgical firms reporting pulverized-fuel consumption to the Mines Department rose from 38 in 1932 to 78 in 1934, and information from individual firms confirms its advantages in particular cases.

The largest users of pulverized fuel for raising steam are the authorized electricity undertakings (*Fig. 8*), and the percentage of their total coal consumed in pulverized form has risen from 7·1 per cent. in 1929 to 16·3 per cent. in 1934, chiefly in large installations. The quantity of pulverized coal used by the collieries was only 5 per cent. of their total consumption in 1934, but in actual tonnage it is steadily increasing (*Fig. 8*). Commercial firms, however, still draw on pulverized coal for a small fraction only of their fuel-requirements (*Fig. 8*).

The chief factor governing the extension of the use of pulverized fuel is the price of small coal. Generally speaking, the larger grades have commanded the readier sale in the past, while the small coal and slack, necessarily raised at the same time, have been difficult to dispose of; consequently they have been offered on the market at a lower price. The difference in price between the grades of coal has been great enough to justify certain consumers in investing in the mills and equipment required, which may include a "grit" removal plant, but the capital expenditure necessary has deterred

Fig. 8.



GROWTH IN THE USE OF PULVERIZED COAL IN INDUSTRY.

small undertakings from turning over to pulverized fuel. Pioneers among coal distributors have sought to meet this situation by establishing central pulverizing plant and undertaking the delivery of the coal to the customers in tank-wagons.

These factors account to a large extent for the trends in the adoption of pulverized-fuel firing, but the story is not solely an economic one. It has proved difficult to burn pulverized coal with a short flame, and a large combustion chamber has been considered necessary for complete combustion. Technical considerations have therefore contributed to the direction of development; to-day,

96 per cent. of the fuel is burnt in water-tube boilers, and 67 per cent. in those of a capacity of over 75,000 lbs. of steam an hour.

E. Audibert set himself the task of discovering whether such large furnace chambers were essential, and whether the difficulties experienced in firing cylindrical boilers were, in fact, due to the confined heating space. Measuring the time of combustion for a variety of fuels under controlled conditions in the laboratory, he found it to vary according to the nature of the coal from 0·2 to 1·0 seconds, and calculated from these results that the space required to burn 1 ton of coal an hour was only 3 to 15 cubic metres. In industrial practice at that time, combustion spaces of the order of 40 to 60 cubic metres per ton per hour were used and attempts to increase the load invariably led to incomplete combustion ; yet there could be no doubt that the particles of coal spent long enough in the furnaces for complete combustion. Audibert suggested that this anomaly arose from imperfect design of the combustion space, which appeared to consist of three zones : (*a*) a dead space in front of the fuel inlet, which served no useful purpose but was nevertheless a large proportion of the whole, (*b*) an ignition-space, which was unnecessarily large, and (*c*) the combustion area proper, which could not be used to the best advantage without damaging the refractory walls. From this analysis he concluded that the dead space could be eliminated by introducing the pulverized-coal particles at as low a velocity as possible, and by keeping the area of the burner-opening small in comparison with the surface of the surrounding furnace walls. The ignition space should be reduced in size by conserving the heat received by radiation from the walls ; this could be achieved by introducing only sufficient air with the fuel to start it burning, and maintaining a secondary air-supply to complete combustion.

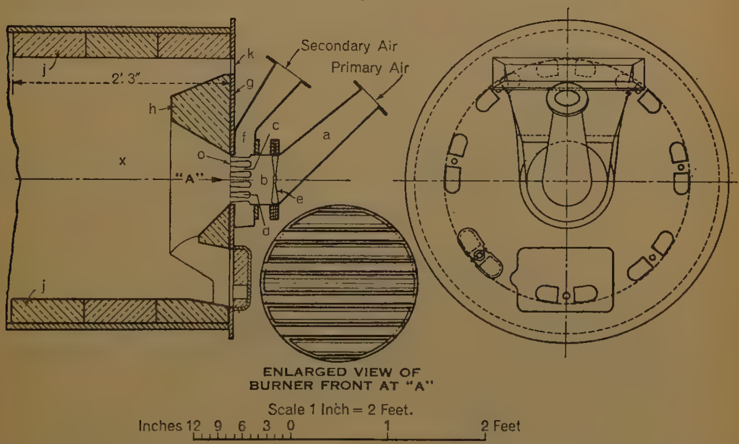
The elimination of dead space and the reduction of the volume required for ignition, essential if pulverized-coal firing was to be made possible in small combustion chambers such as those of the Lancashire boiler, were primarily questions of burner-design. To meet these conditions, experiments have been carried out at the Fuel Research Station and have resulted in the burner illustrated in *Figs. 9*.

The pulverized coal is carried forward by primary air from an inclined supply-pipe (a) into a short horizontal chamber (b). The mixture then passes through a number of long narrow slots (c) into the combustion chamber (x). The slots are of venturi shape and are formed by the walls of the ducts (d), by which the secondary air supply passes from the box (f) into the combustion-chamber through the narrow openings (o). Radiation from the surface of the cone of brickwork (h) and the cylindrical ring (j), which extends

2 or 3 feet into the flues, induces ignition. A novel feature of the design is the provision of a tertiary air supply through ports (k) in the front plate.

The sharp bend in the primary-air supply-line immediately before the burner mixes air and fuel thoroughly and distributes them well across the face. The rapid acceleration and deceleration of the primary air as it passes through the nozzles improves the mixing. This use of slots of venturi cross section introduces a rich mixture into the furnace at a low velocity, and yet guards against the possibility of back-firing into the primary air supply. Stratification of the primary and secondary air supplies secures rapid ignition, and yet provides for the complete combustion of the volatile matter, as it is evolved, and of the solid particles when the limited supply of

Figs. 9.



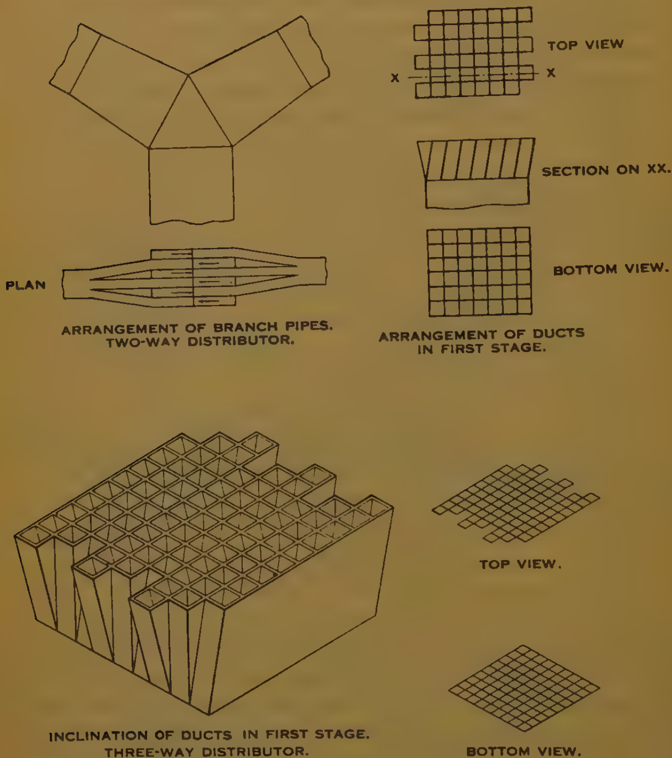
primary air has been consumed. Should any particles coarse enough to be sensibly affected by gravity be present in the fuel, they have only a short distance to fall to an atmosphere of undiluted air. The way in which the tertiary air is introduced has two effects. As combustion proceeds, more air can be introduced progressively, yet quickly, without lowering the flame-temperature, and the supply can be so regulated that the brickwork is kept below the temperature of fusion-point of the ash, thus reducing maintenance-costs whilst still providing a large radiant surface to aid ignition.

A further development of the above principle has been designed, known as the "multijet" burner. Essentially, this is a "grid" burner that is provided with an additional set of secondary air-openings intersecting the original slots at right angles, so that the stream of fuel and primary air mixture issuing from each nozzle is

completely surrounded by a secondary air supply. Although the "multijet" is rather more difficult to construct than the "grid" burner, the advantage of making secondary air more readily available after ignition results in practice in a distinctly hotter and shorter flame at low loads.

Before giving some account of the results that have been achieved

Figs. 10.



with these burners, there is another device that should be mentioned. This is a distributor (*Figs. 10*) by which the air-borne fuel can be divided into two or more streams to serve a number of burners. As the distribution of fuel across the original stream is not uniform with respect both to concentration and particle size, its division into equal parts has been found extremely difficult. The duct of the new distributor is square in cross section and is partitioned into a number of smaller squares. The way in which the fuel from alter-

nate sub-sections is collected into the divided streams can best be understood from the diagrams.

The "grid" burner has been used successfully to raise steam in Lancashire and in Babcock and Wilcox boilers over long periods with little supervision. If necessary, all three supplies of air can be pre-heated; this was found to be advantageous when burning Welsh coal with only 15 per cent. volatile matter, but was not found necessary when using coals with 20 per cent. Satisfactory operation has been obtained with fuels containing from 20 per cent. to 35 per cent. of volatile matter, and efficiencies of 74 per cent. have been maintained in a Lancashire boiler without a pre-heater or economizer.

These trials were carried out when evaporating steam at the rated load of 5,000 lbs. per hour, but just recently it has been found possible at the Fuel Research Station to raise the load to 10,000 lbs. of steam per hour, without the efficiency falling below 68 per cent. Indeed, as this difference can be largely attributed to a higher flue gas temperature, 835° F. instead of the 590° F. at rated load, it should be possible for a commercial installation, fitted with a larger economizer than is normal, to work at the same efficiency with 100 per cent. overload as at the rated load. Promising results when working under such conditions have already been reported from outside firms.

No discussion of the development of pulverized-fuel firing, as applied to steam-raising, would be complete without reference to the problems of purifying chimney gases. As the damage to health and property, which the emission of acid gases may cause, becomes more widely realized, we may expect control to be extended more generally in densely-populated areas. When the Battersea power station was projected, efficient centrifugal dust-arrestors, electrical precipitators and wet washers were in common use, but no methods of removing acid gases had been developed on such a scale. The process adopted was a scrubbing with warm water in horizontal flues, followed by water-sprays and an alkaline liquor treatment in vertical flues. The quantity of sulphur gases escaping into the air has been reduced to 0·03 grain (S as SO_2) per cubic foot.[1] As far as its general application goes, this method has the disadvantages that the water-consumption is high, and that excessive cooling of the flue gases lowers unduly the velocity at which gas escapes from the top of the chimney.

A second process,[2] which has been described in detail by Dr. J. L. Pearson, Mr. G. Nonhebel and Mr. P. M. N. Mander, substitutes

[1] Reports of the Government Chemists' Committee. Published by H.M. Stationery Office, 1931, Cmds. 3714 and 4771.

[2] "The Removal of Smoke and Acid Constituents from Flue Gases by a Non-Effluent Water Process," Journal Inst. Fuel, vol. VIII. (1934–35), p. 119.

scrubbing with alkaline liquor for water. A chalk or lime sludge is continuously recirculated through towers with grid packing, so that the water-consumption is considerably reduced. The rate at which fresh lime is added is determined by observation of the p_H value of the circulating liquid. The calcium sulphite first formed is oxidized to calcium sulphate, which forms a supersaturated solution in the scrubbers. Crystallization on the packing and the walls of the vessel is prevented by the presence of a large percentage of $CaSO_4 . 2H_2O$, and de-supersaturation is completed in a delay tank.

Professor H. F. Johnstone[1] has developed at the University of Illinois another system of liquid washing, in which the SO_2 is absorbed in ammonia solution at 95° F. This method is particularly interesting, since the SO_2 can be recovered by heating to a higher temperature and so can be regarded as a potential credit for commercial disposal. It is understood that a large-scale experimental plant is to be erected at one of the Chicago power stations.

Despite the success of these methods, there is still scope for methods that can be applied to the flues of furnaces where relatively small quantities of fuel are burnt. Where no purification is practised, the contamination of the atmosphere depends on two factors, the sulphur and ash the coal contains and how much coal is burnt. A small station, if isolated, might escape the need for purification if carefully-cleaned coal was burnt. But where many small furnaces are concentrated, the cumulative effect is considerable, and, as pulverized-fuel firing extends, so will the necessity for dust-removal. Experiments on simple methods of removing dust from flue gases have been started at Greenwich, but have not yet reached the stage where they can be reported.

When this Paper was projected, it was proposed to describe the hydrogenation experiments which have been carried out at the Fuel Research Station, but the length of the Paper has grown to such an extent that it has been decided to leave this subject for some future occasion, when perhaps The Institution may honour a member of the Fuel Research staff by asking him to prepare a Paper. A few general observations may be allowed, however, based upon the broad considerations that have emerged from the work at the Fuel Research Station.

Besides the practical merit that greater throughputs and therefore higher yields from unit volume of catalyst can be obtained, high pressure may be essential to make the reaction proceed, or its main advantage may be the avoidance of disturbing side reactions. The

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[1] "Recovery of Sulfur Dioxide from Waste Gases," *Industrial and Engineering Chemistry*, vol. 27 (1935), p. 587.

ammonia-synthesis is, of course, a clear-cut realization of thermodynamic principles. In the formation of methyl alcohol from carbon monoxide and hydrogen, the importance of pressure is not solely that less alcohol would be formed without it, but that with it the production of methane can be avoided.

At first sight the use of pressure, when cracking heavy oil to petrol, seems contradictory, as the reaction results in an increase in the number of molecules, but its main reason is again thermodynamic, since the formation of gaseous instead of liquid hydrocarbons is repressed. On the other hand, when oil is hydrogenated to give lubricating oil of high quality, by working under pressure the reaction can be carried out at temperatures low enough to avoid loss through cracking.

In the conversion of coal and tar into motor-spirit, however, both hydrogenation and cracking reactions are necessary. Partial hydrogenation of the complex aromatic material is a necessary preliminary to its breakdown by cracking to simpler hydrocarbons, and will be facilitated by pressure. On the other hand, the value of the product as motor-spirit is lowered if further reduction of benzene homologues to naphthenes takes place. This is uneconomical, since hydrogen is wasted by allowing the aromatic hydrocarbons to be converted into naphthenes. To take a simple example, six additional hydrogen atoms are required to convert benzene into cyclo-hexane, although benzene is more valuable as a motor fuel than cyclo-hexane. The danger of this conversion taking place is lessened by working at high temperatures, when there is a tendency for de-hydrogenation to take place. Such conditions, however, favour the formation of excessive amounts of gas and may lead to coke-formation.

High pressure is not only essential to maintain the delicate balance between hydrogenation and cracking, but when treating tar it also reduces effectively the rate of deterioration of the catalyst. The general effect of pressure on the percentage conversion of low-temperature tar into motor-spirit boiling below 200° C. is given in Table I, which contains figures obtained during experiments carried out at the Fuel Research Station.

The chief lesson learnt at the Fuel Research Station is the ease with which high-pressure plant may be operated, even although the scale is quite considerable. An experimental plant capable of treating 300 gallons a day has been erected at the Station, and it has been found easy to maintain it in first-class condition and to control and operate it. In the discussion of the economics of Imperial Chemical Industries Ltd.'s hydrogenation plant at Billingham, there is a danger that its outstanding importance as a technical achievement of the first order may be lost to sight. The plant is a great example of

chemical engineering and the whole technique merits the closest study by engineering students.

The object of the Paper has been to review a small number of questions which are exciting the interest of fuel technologists. The subjects selected are concerned mainly with the treatment of coal,

TABLE I.

Temperature.			Pressure in atmospheres.				
			100	150	200	300	400
480° C.	Cold start	Sp. gr. at 15° C. of liquid product	0·895	0·886	0·867	—	0·847
		Per cent. spirit boiling below 200° C.	35·4	36·3	40·5	—	42·2
,,	Hot start	Sp. gr. of product	—	—	0·884	0·872	0·870
		Per cent. spirit boiling below 200° C.	—	—	35·4	37·6	37·8
510° C.	Cold start	Sp. gr. of product	—	—	0·858	—	0·816
		Per cent. spirit boiling below 200° C.	—	—	46·5	—	56·0

since this branch of fuel technology is sometimes overlooked in the greater interest associated with combustion or carbonization. Other subjects from the programmes at the Fuel Research Station might have been treated, but the whole of the processes for the utilization of coal are dependent to a great measure upon its properties and preparation, and it is for this reason that particular attention has been paid to them.

The Figures in this Paper are the copyright of the Crown. *Figs. 2, 6, 7* and *10* are reproduced from the Annual Report of the Fuel Research Board for 1935, and *Fig. 9* from Fuel Research Technical Paper No. 36, by permission of the Controller of His Majesty's Stationery Office.

The Paper is accompanied by nine sheets of drawings and one photograph, from which the Figures in the text and the half-tone page-plate have been prepared.

Discussion.

The AUTHOR, before introducing his Paper, said that he thought at all concerned with the subject of coal would like him to say a ord about the late Professor J. S. Haldane, who had recently ed. Professor Haldane had been one of the most learned en on the subject of coal. His were really the basic researches which most of the knowledge of the oxidation of coal d been built. He had been the first Director of one of the first search associations ever formed, namely, the Doncaster Coal wners' Research Laboratory, the object of whose work was to idy the problems of safety in mines. Those who had had the nour and pleasure of knowing Professor Haldane regarded him as a ost exceptional man, because, combined with his great knowledge, had a deep sympathy with anyone striving to gain knowledge of al. The Author.

The Author said that in his choice of the subjects for discussion, had taken care to avoid those that had been dealt with in the three dresses which had been presented within the last 18 months; mely, one given by Sir Richard Redmayne as President of The stitution,[1] one given by Sir Frank Smith [2] quite recently—a narkable study on the subject of coal and its uses—and one given Sir Harold Hartley.[3] He thought it might be of interest to cuss one group of problems which he considered was of very great portance; namely, problems connected with the preparation of w coal for the market, its use in the raw state, and its use in the lverized form. He had also given at the end of the Paper a very ef history of the technique of hydrogenation.

The group of problems with which he had dealt were of growing portance, and were extraordinarily rapid in their development. was now becoming widely realized that a new science of coal-eparation had arisen. Whereas 15 years ago coal had received quite ough treatment in order to prepare it for the market, nowadays treatment was the most scientific possible. Therefore preparan for the market as a scientific subject required the attention of th scientists and engineers.

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1 Minutes of Proceedings Inst. C.E., vol. 239 (1934–35, Part I), p. 3.

" Coal, Power and Smoke," Presidential Address to the Junior Institution ngineers, 13 Dec., 1935.

" Our National Coal Researches," Hinchley Memorial Lecture to the Instiion of Chemical Engineers, 25 Oct., 1935.

The Author. First, there was the question of the coal seams themselves. his Paper he had given a brief description of the Coal Surv which was now proceeding throughout the country, and the was one particular fact which he desired to emphasize, that eve sample was personally obtained by an officer of the Departme of Scientific and Industrial Research. That duty was nev deputed to anybody else. The sample was put in a sealed b by the officer, taken to the laboratory, one of which was fou in each coal area, and within 24 hours the first series of determin tions was started, so that no variation in the coal should be possib The importance of the task could best be appreciated from example; there was actually 80 feet of thickness of coal in workal seams in Lancashire and Cheshire, and the field covered an area 500 square miles.

Turning to the subject of coal-cleaning, he remarked that I C. H. Lander and himself had become extremely interested coal-washing in 1924, and as a result an experimental washer h been erected at the Fuel Research Station which, he thought, h served a most useful purpose. A great deal of the advance whi had taken place in the washery-technique of Great Britain could put down to its installation. He pointed out that there were now the British market very large quantities of washed coal, which ha minimum percentage of ash. He was certain that that was the c to use.

In discussing the combustion of pulverized coal he drew attenti to certain interesting characteristics of the burner shown in *Figs.* One was that the coal was mixed with a certain proportion of not enough to cause an explosive mixture, but yet sufficient to br about primary combustion. He had originally intended to disc in the Paper the burning of coal, but had been persuaded to omit remarks on the subject; his point, however, was that there was urgent need for knowledge of how coal burned in the form of a parti When Dr. Lander had been at the Fuel Research Station, he had gi particular attention to that subject, but unfortunately no one now looking into it with the care that it demanded. The reas why the Author was emphasizing that point was because at distant future a pulverized-fuel engine, burning coal in place petrol and oil, might be available and, if that engine was going work, the principles of the combustion of particles of coal must understood. He was keeping in touch with two authorities Europe who were developing pulverized-fuel engines, working o diesel cycle and burning coal-dust, and that research had b brought to an advanced stage. That brought him to the point w which he had started, namely, that a study would have to be mad

The Author.

ie way in which the different coals which were available could be urnt.

Sir Richard Redmayne.

Sir RICHARD REDMAYNE congratulated the Author on his explanaon of what was being done at the Fuel Research Station, and on is indication of what had been done in the past and what it was itended to do there in the future. It seemed to him that the hole Paper was based on the opening words, "During the past few ears the elimination of wasteful methods in the utilization of coal as become the pressing concern of nearly every branch of industry."

In the year 1911 it had occurred to him that something should e done in regard to the elimination of waste, and he had written Minute; the Minute was revived in 1916, and the Coal Conservation ommission was formed. That Commission reported in 1918. The te Lord Haldane had been Chairman, with Sir Richard, a member of ie Commission, as his general assistant, and the Commission comrised men who were qualified to investigate the whole position ientifically. Lord Haldane had sent him to consult Sir William acCormack and Sir Frank Heath, and the result had been the rmation of the Fuel Research Board, now so ably presided over y the Author, by Dr. C. H. Lander before him, and previously by ir George Beilby. Dr. R. V. Wheeler had drawn Sir Richard's tention to the fact that there was no chemical survey of the coalelds of Great Britain, and so one had been set up within the Fuel esearch Board. In that connection it would be seen what was being one with the coalfields of the United Kingdom. The work was, erhaps, belated, but it would be one of the finest, most useful and ghly economic pieces of work which a scientific body could underke.

Much of interest was emerging from that Chemical Survey, but ie point puzzled him; mention of it would be found in his article 1 "Coal and Coal Mining" in the *Encyclopædia Britannica*.[1] He ould ask the Author to give his explanation of it. Dr. Sinnatt had ated in his Paper that there was a gradation, from east to west, the great South Wales coalfield, of the passage from bituminous al to steam-coal and to anthracite, and thus with a continual duction towards the west of volatile hydrocarbons contained in e coal. It would naturally be thought that the ash-content ould increase, but the reverse was the case. He would not give s own explanation, but he would be very interested to hear the ithor's explanation.

The Author had alluded to a number of methods of using coal. e had alluded, in passing, to the question of low-temperature rbonization. Low-temperature carbonization was, through the

[1] Fourteenth edition (1929), vol. 5, p. 868.

Sir Richard Redmayne.

courage of one or two men—notably Colonel W. A. Bristow—emerging from trial to success, and he looked forward to the da[y] when a large part of the petrol that was used in aeroplanes and car[s] and of the oil that was burned by the Admiralty, would be supplie[d] from home sources. Sir George Beilby used frequently to allude t[o] the fact that, if the whole of the coal used in domestic hearths i[n] Great Britain, namely, from 35 to 40 million tons per annum, we[re] subjected to low-temperature carbonization, there would be enoug[h] oil to supply the British navy in times of peace, and the output [of] coal per annum would be about 13 million tons more. An enormou[s] quantity of petrol would also be produced, but not sufficient for th[e] country's needs. As Sir Frank Smith had explained,[1] such a chang[e] would bring about an enormous decrease in the amount of soot an[d] dust discharged into the atmosphere, and would thus save millions [of] pounds per annum by the elimination of smoke.

Only certain coals were suitable for low-temperature carbonizatio[n] and persons and companies considering the question of low-temperature carbonization on a big scale would have to pay atten-tion to the chemical survey; they would have to build their factori[es] in places where the coal was of a suitable character if they wishe[d] to save long-distance transport.

With regard to the three main methods of cleaning coal, namel[y] the wet method, the dry or pneumatic method, and the froth metho[d] he had had a good deal to do with the froth-floatation proces[s]. That was an excellent process, but it was expensive. The pneumat[ic] method seemed to him to be most generally useful in the case [of] stainable coals and it was achieving a considerable success, but t[he] method which he liked the best, given an ordinary coal, was the ol[d-]fashioned Beaum washer. It was very hard to beat the performan[ce] of that type of washer, and he always advised its application, unle[ss] the coal to be dealt with was especially liable to stain under th[at] method.

He was pleased to hear of the work which was being done at t[he] Fuel Research Station in the matter of pulverized coal, and [he] thought that it was a most appropriate piece of work for the Fu[el] Research Board to undertake. He hoped that the considerab[le] difficulties that had had to be met in the utilization of powder[ed] fuel would be completely eliminated by the work which had be[en] carried out at the Fuel Research Station.

Dr. Lander.

Dr. C. H. LANDER remarked that, as the Author had referred [to] the association which he had had with him for many yea[rs]

[1] "Industrial Research and the Nation's Balance Sheet," Norman Lock[yer] Lecture to the British Science Guild, 1932.

articularly as regards the Coal Survey, he desired to say a few ords on that subject. Dr. Lander.

When he first came into contact with the idea of the Survey, Sir ichard Redmayne had been a member of the Fuel Research Board, gether with Sir Richard Threlfall and Sir Charles Parsons. Sir eorge Beilby was the chairman of the Board and was Director of uel Research. As Sir Richard Redmayne had just said, he (Sir ichard) and his colleagues had been responsible for initiating the irvey, and Dr. Lander, as Sir George's assistant, had been given the sk of organizing it. He could, however, get no interest taken in at all by the industry. It had been looked upon with suspicion all the coal-producing centres, and he had been almost in despair getting it started. He knew the Author, who was very enthusi-tic about the matter, however, and together they started the Coal irvey in the Lancashire area. The Author had been the Director Research to the Lancashire and Cheshire Coal Research Associa-on, the members of which were enthusiastic; a laboratory was arted, and matters went well in that district. The Survey could ot be expanded, however, as although another section had started Sheffield, it did not spread any further. That had been the osition about 1926. After the coal strike in 1926, a Bill had been troduced into Parliament which led to the Mining Industry Act of 927. There had been so much argument about other things that had not been noticed that those interested had slipped into that ill a clause which gave the Department of Scientific and Industrial esearch the power to demand any samples they wished, under a onetary penalty from the management. He believed that that ower had never been used, but from that time the Survey had gone head, and it was now firmly established.

There was one point to which he desired to refer, and that was ith regard to what the Author had said about the study of the way which coal-particles burned. Dr. Lander thought that what had een stated in the Paper was quite inadequate. For instance, on 558 the Author referred to the time of combustion for a variety of els under controlled conditions in the laboratory as varying, cording to the nature of the coal, from 0·2 to 1·0 seconds. Particles coal might take that time in certain circumstances, but the whole oblem was very much wider than that. When carbon was burned th oxygen the velocity of the oxidation-reaction was extremely eat, and on that ground it did not control the time of burning. ie actual control was exercised by the diffusion through the so-called stationary layer"; the rate of burning could be increased by inning down the "stationary layer," and that was the sole ason why a fire could burn more rapidly by the action of forced

Dr. Lander. draught. There were certain types of chemical reactions whic could not be " blown up " by increasing the velocity of the gas passir over the surface, but the combustion of carbon was not one of tho types. A particle of carbon was just in the same state, with regar to the amount of air necessary to burn it, as a lump of coal; that wa to say, it required about 12,000 times its volume of air measured a atmospheric temperature; when the air got into the furnace, th volume was very much larger than that. That meant, in proportio that a lump of coal of about 8 cubic feet would require all the air i a very large room to burn it. How did the engineer burn that piece coal? He broke it up into suitable sizes, put it in a grate, and brougl the air to it, thus scrubbing off the " stationary layer "; the fast he could bring the air to it the faster it burned, within limits. Even i a grate it was possible to obtain a range of a hundred times in th speed of burning, whereas the range given in the Paper was only fiv times. The particle was in just the same position. It required fo its combustion a large quantity of relatively inaccessible air, and tha air had to be brought within a certain distance of the surface; had to be made to diffuse through a layer which was always presen The only way in which it was theoretically possible to obtain th maximum speed of burning was by making the coal-particle move i such a manner that it was scrubbed. That was a very difficult matte because a particle so easily acquired the speed of the stream of air i which it was caught. If it was in a stream-line it was carried alon and the result was a long " lazy " flame. The obvious thing to d was to give the air turbulence, as, the particle being heavier than ai it would then be thrown out by centrifugal force from one eddy t another and would therefore be scrubbed. But there was a limit t what could be done by turbulence, which mixed up the products o combustion with the fresh air so that at the same time as relativ motion was given between the particle and the air, the air wa being contaminated with gas from the particle. That went o progressively down the flame, and combustion again slowe down.

For maximum speed of burning, the problem really was to dete mine a method enabling a more definite result to be obtained. F had shown that if an air-vortex of the " wash-basin " type we arranged and coal were dropped into it at a suitable point, a form rotating " bed " would be produced, the coal tending to drift acro the air but being held in position by the radial component of the a which was going down the vortex; on the one side of the coal the was, therefore, fresh air, and on the other side there was the flu gas. The bed thus formed was just as definite as the ordinary b of a fire. When Director of Fuel Research he had obtained sor

ry high heat-releases by that method, and an imperfect application it was the so-called well-type furnace. Dr. Lander.

Dr. Lander emphasized that that method of dealing with the oblem should be developed very much more extensively than was ing done at the present moment, because it introduced such ormous possibilities. If certain calculations were made with gard to industrial appliances, it would be found that operations hich might at present take a structure 80 feet in height could eoretically (but not, as yet, practically) be done in a space of a w cubic yards. When, therefore, there was such a wide difference was surely worth while investigating to see whether the size of me of the present heat-using appliances could not be reduced om their present size if pulverized fuel were burned; that would cessitate the fuel being burned with regard to the above funda-ental laws.

Dr. E. F. Armstrong, speaking as a consumer and not as an Dr. Armstrong. gineer, desired to say what good service the Author had done in nphasizing the importance of the selection of the right kind of al for the purpose in view, and in promoting the work of the Fuel esearch Coal Survey. It was probably well known that for a nsiderable number of years past a group of London gas-companies d had a testing laboratory at Newcastle, adjacent to the coal-lds, which had made it possible for them both to select the most itable coals for gas-making, and to sample and grade each coal it was delivered on the steamer, so that its exact nature was own when it arrived in the Thames; the gas-companies were so enabled to influence the collieries to produce more suitable als. Thus, over a period of years the average ash-content had en reduced by one-half, enabling real economies to be made in nsport, in retort through-put and in the disposal of ashes. For ample, assuming that, at the start, there had been 10 or 12 per nt. of ash, then, approximately, one steamer in every nine carried ly ash, or waste matter, from Newcastle to the Thames. As a ult of the Survey, however, at the present time only one steamer eighteen or nineteen carried waste matter in that way. In dition, the selection of the right coal had resulted in the production a larger number of therms of gas per ton of coal carbonized. It uld be agreed that the work of such a station had more than tified its cost; that case was an example of what the Author had en emphasizing, and showed what could be done in selecting and lizing coal to the best advantage.

He was one of those who thought that it was wrong to burn coal ectly, except under special circumstances where it was necessary to al with pulverized fuels, and he deplored the failure on the part of

Dr. Armstrong. the State to encourage the use of gas, which was all the more mark because of the help given to the use of electricity by the State, t County Councils and the Municipalities. Gas was the ideal mea of transporting potential heat in concentrated areas; the custom required no stocks, and had no residue to discharge, while o series of mains supplied everyone, and the streets were not block with coal-delivery lorries. Gas was the ideal way of utilizing co and its use ought to be encouraged by the Fuel Research Boar and in every other official way, so that its cost might be reduce The gas industry was one of the best customers of the coalfield because it bought from the collieries their best coal. It was ve sad to see that the Coal Utilization Council generally considered g as its rival, instead of regarding it as the proper form in whi coal should be used.

He desired to refer also to the valuable work on high-pressu hydrogenation done at the Fuel Research Station, and he thoug that it should be encouraged in every possible way. The gre venture at Billingham had its critics on the economic side, but did not think that that side should concern engineers or chemis at all, because it was so extremely important for engineers in Gre Britain to gain actual practical knowledge of high-pressure techniq and of the handling of large quantities of gases and liquids. Unle the chemical engineers of the country were given that opportuni there was the risk of not keeping up with the developments in t latest branch of applied chemistry, and engineering firms wou then lack the experience to make the necessary plant. Few w had not actually seen the United States oil-refining industry cou appreciate either its magnitude or the courage of its designers a operators, or the advance in constructional materials which represented. That knowledge must also be brought to Gre Britain.

Dr. Lessing. Dr. R. Lessing said that the Author had not only dealt with t survey of the physical and chemical character of the coalfields b had himself given a survey of another kind which covered the wh field of investigations carried on at the Fuel Research Station. It w quite impossible for Dr. Lessing to touch on many of the points rais in the Paper, seeing that the Author himself had been unable in t time available to do justice to all the important matters which he h brought forward. Dr. Lessing would, therefore, confine himself t few points only.

He had always emphasized the advantages of clean coal, and it w satisfactory to learn the extent to which cleaning by one method another was now being practised. The Mines Department had be collecting statistics of the tonnage of coal cleaned for nearly 10 yea

Dr. Lessing.

e would suggest that the time had arrived when, in addition to the umber of cleaning-plants and the tonnage of coal put through ose plants, some index of performance should be recorded in the atistics, from which it might be possible to estimate the degree of urification which the coal had undergone in those installations. He oped that the Author would pardon him if he ventured to cast a little oubt on the statement made in his introductory remarks that the esent products from the cleaning-plants really contained a minium of ash. Dr. Lessing thought that there was still a long way to o before reaching finality, and he would like to point out that mere duction in ash-content from the raw coal to the marketed coal was ot the only consideration. The diversity of properties in the various ctions of the coal-seams and in their sub-sections, to which atten-on had been directed, showed that it would be necessary in future separate the products of any particular colliery, and even the fferent components of a single seam, and to divert each kind of coal to the channels in which its particular properties could be utilized the best advantage. He could not go into very great detail, beyond inting out that the characteristic differences did not relate only the coal-substances, but also in a large measure to the various nds of mineral matter present in the original coal and to those left the coal after it had gone through the preparation-processes.

The importance of the size of coal was only just beginning to be alized. Dr. Lander's instructive remarks on the question of ulverized fuel applied to the same extent to the more massive part the coal, that was, to the coarser coal-particles. Dr. Lessing lieved that within a very short time every user would realize the eat importance that must be attached to sizing, and it would then brought home to the coal-producer that, after all, he had to supply hat the consumer and the consumer's appliance required for its best rformance.

Some mention had been made about coal-dust firing and preparing e dust by pulverizing the larger sizes of coal. It was, however, not preciated to a sufficient extent that about 7 or 8 million tons of tural dust were being produced in Great Britain each year. The uthor had mentioned a similar figure when referring to fine coals aller than ⅛ inch, but Dr. Lessing believed that a proper survey of es would show that at least 7 or 8 million tons of dust smaller than inch were available. That was important for reasons other than e actual chemical and physical properties of the particular variety coal represented in the dust; in particular, it was very important m the view-point of combustion. If proper statistics of the atter were available, he thought that it would be found that the ount of that dust was of the same order of magnitude as that

Dr. Lessing. which, after combustion, complete or partial, was going out into th atmosphere as atmospheric pollution. The aerodynamical problem and their explanations put forward by Dr. Lander dealt with th combustion-conditions in a furnace which had to bring about th combination of oxygen with the coal at a very high velocity of passag through the fuel-bed, and it would be readily understood how easil the dust could be raised before complete combustion had occurred.

Whilst dealing with atmospheric pollution he wished to refer to th second process of sulphur-elimination from flue-gases mentioned o pp. 561–2 of the Paper. A slight mis-statement in the proof, sinc corrected by the Author, had given him the opportunity of stressin the importance of counteracting the phenomenon of supersaturatio to which the solutions in a cyclic process were liable. Having bee personally responsible for the fundamentals of that process, he woul like to make it clear that, in the elaboration of the process, it ha been found that, instead of delaying crystallization of calciu sulphate, it was essential to induce crystallization as rapidly a possible by suspending a large percentage of calcium sulpha dihydrate in the liquor, which until then had been considered a sour of danger in causing clogging of the scrubbing devices.

Mr. Pirie. Mr. H. L. Pirie said that the Paper was extremely valuable t those whose duty it was to promote the use of coal by efficient an economic means. Reference had already been made to the selectio of the right coal for the purpose in view. Translating that in more commercial language, he presumed that it meant that coa selection must precede coal-purchase. That, in his opinion, wa of very great importance, because any appliance would burn a coals with some degree of satisfaction but no appliance would bu every coal satisfactorily. It was therefore necessary to determi those coals which would work successfully in any given applianc and to exclude from consideration those which were not suited it. He was quite sure that, although the problem was a difficu one (and combustion-engineers had applied themselves to it), t Coal Survey facilitated the work. In his opinion, however, it d not go quite far enough; he suggested that it should be possible get from every colliery accurate particulars of the various sea which it worked. He did not know, however, whether the Depa ment of Scientific and Industrial Research would be able to ca that out. Sizing was also very important; it might be of inter to know that in one coalfield the colliery-owners had conside that there were too many sizes, and they had appointed a co mittee to reduce their number if at all possible. It had been fou that in that particular field there were more than one hundr sizes below 3 inches, and it had been possible to reduce that numb

o fifteen without apparently being detrimental to any of the ollieries concerned. Mr. Pirie.

In reference to the remark of Dr. Armstrong regarding the Coal Jtilization Council being hostile to the use of gas, he would point ut that the Coal Utilization Council was supported by every olliery producing gas-coal; it was, therefore, wrong to say that hat Council was antagonistic to the use of gas or of any derivative of oal.

Mr. J. G. Bennett remarked that the work described by the uthor was of great national importance, and his Paper raised the hole question of the adequacy of the means available in Great ritain at the present time for investigating fuel-problems. Mr. Bennett.

In every kind of research there were usually three phases, the first f which consisted in isolating the problem to be solved; the second, discovering the best means of attacking it, and the third in comleting the research. Expenditure on research during the first two ages might be attended with risk, because there might be failure recognize the kind of information which was required and, even this was understood, time might be lost and much money might e spent in discovering the right technique; false starts might be ade, and it was even possible that the problem might prove capable of solution with the means of investigation which were ailable at the time.

The third phase of research differed fundamentally. The researchorkers knew where they were going and how to get there, and the k of unavoidable failure was eliminated. Failure could then only cur if the research-workers were prevented from completing their ork through lack of sufficient resources of man-power or money. mong the lines of research which the Author had presented, veral had reached the third phase; that was to say, their complete ccess was only a matter of sufficient money and time. That ferred particularly to the first section of the Paper dealing with e Coal Survey. It had been proved by more than 20 years' work at it was possible to obtain accurate and reliable samples of the al-seams of Great Britain, and that their physical and chemical operties could also be obtained. The variation in those properties ross the seams could be determined and plotted on charts. It was rcely necessary to emphasize the value of that work, but he wished add that, from his own experience of the problems which arose the design and operation of appliances in which coal was used, it s of vital importance. In Great Britain the coals were not always d for the purpose for which they were most suited, and loss of ciency resulted from such misuse. Another result was decreased trol over the process of combustion and other processes in which

Mr. Bennett. coal was used, and that led to otherwise avoidable failures of installa-tions. That misuse also had many secondary consequences, such a increased atmospheric pollution, and it aggravated the problem of th disposal of effluent. It was no exaggeration to say that the loss t Great Britain annually by failure to use its coals for the purposes t which they were best suited was many millions of pounds. He di not suggest that the completion of the Survey would entirel eliminate that loss, because cost of transport and difficulties c distribution must always limit the extent to which coals could b allocated to ideal markets, but he did assert that the benefits woul be very large indeed, amounting to a sum very much more tha the Survey was costing now. Besides that, the Survey was necessar for the solution of many other important problems, such as th best conservation of the national fuel resources, the technica classification of coals, the planning of industries for the distresse areas, and other matters of national importance. A task of nationa urgency was, therefore, before the Survey, and he would like t know how soon it would be completed. The Author had not give estimates of that, but if he were to do so Mr. Bennett thought tha it would be found that the rate of progress was not as fast as woul have been wished.

He had said that the progress of research, when it reached th phase of completion, was dependent on resources of man-power an money, because highly-trained workers could not be procured b money alone. He would therefore like to know whether, in th Author's opinion, the staff of the Coal Survey could within a reaso-able time be increased to three or more times its present numb so that the work could be completed in one-third of the tim necessary under the present conditions. From his own knowled of the fuel-research stations which he had visited, Mr. Bennett ha no doubt that such was the case. The technique of the Survey w so well established, and the officers had gained such long and com-plete experience of the work, that additional workers could b drafted in from the universities and technical colleges and, und the guidance of the present staffs, the work might be pushed forwa as quickly as finance would permit.

He would have liked to have said a great deal about the rest of t Paper, in which the Author had dealt with the problems of co preparation, combustion, and the performance of appliances in whi coal was used. Those were all problems with which he was co-stantly faced, and he had become convinced of the need for a great degree of centrally-organized co-operation than had existed in t past between producers, distributors, consumers, and makers appliances in which coal was burned, on the one hand, and the Fu

Research Station, the Departments of Fuel Technology of the Universities, and coal-research workers generally, on the other. Mr. Bennett.

Whenever the problems of coal-research were considered the fundamental fact had to be remembered that less than 25 per cent. of the thermal energy released in the combustion of coal was recovered in the form of useful work. The loss to Great Britain, as compared with 100 per cent. efficiency was, taking the value of coal at its pit-head price, £105,000,000 per annum. An increase of 1 per cent. in the over-all efficiency of coal-utilization was worth £1,000,000 per annum. Coal was not only a source of thermal energy; it was one of the most important chemical raw materials in the world. Yet only a fraction of 1 per cent. of the coal-substance which was mined found its way into chemical industry. No one taking those facts into account could doubt that Great Britain was only at the beginning of the era of the scientific utilization of coal. The problems involved were so vast and so varied that he did not consider that they could be dealt with adequately until the Government and the industries concerned were prepared to spend at least £1,000,000 per annum on coal-research. The problem was one which should be attacked on a scale commensurate with the importance of fuel and power in the life of Great Britain.

Mr. A. C. WALSH said that he would like to take the opportunity, as a coal-producer, to say how helpful the Fuel Research Board had been in aiding the producers to solve various difficulties which they had encountered from time to time. Mr. Walsh.

With reference to the cleaning and sizing of coal, he might say that the company which he represented had two modern collieries in the Kent field. At one of the pits the coal was dry-cleaned, and at the other it was cleaned by washing. A comparison of the two plants might be of interest. At one colliery the company had been faced with the condition that there were no facilities for getting rid of an effluent, whilst the workings below ground promised to be comparatively dry. As there was sufficient variation in the specific gravity of the coal and dirt, dry-cleaning had been decided upon. A Birtley dry-cleaner had therefore been installed having a capacity of 95 tons per hour. The coal treated by that cleaner ranged from nil up to 1½ inches, and the cleaner was designed to reduce the dirt from 16 per cent. to 9 per cent. The plant had been quite a success, but although many customers appreciated a cleaner coal there had been considerable difficulty in persuading them to pay the extra price necessary to cover the cost of cleaning and to compensate the company for the loss in weight due to the removal of the dirt. However, in the last 4 or 5 years the company had noticed a greater tendency to pay a little extra for the clean product, and they were

Mr. Walsh. now passing a larger proportion of the output of the pit through th cleaning plant. The extra cost of dry-cleaning might be of interes On that particular plant the cost actually worked out at 1*s*. 6*d*. extr per ton, and of that amount 1*s*. 1*d*. was due to the loss of weigh The actual cost of operating the plant was only about 3*d*. per to One objection to placing reliance on a dry-cleaner as the only mea of cleaning coal at the colliery was that even a 5-per cent. moistur content had a strong tendency to prevent the coal from movi freely on the cleaning-tables, and on several occasions the compa had been unable to select a sufficient amount of dry coal to meet t requirements of the cleaner. Later the second colliery came on production. This was clearly going to be a wetter pit, and as the was a small stream in the vicinity capable of taking a limited amou of effluent, it was decided to wash the coal rather than to dry-clea it. For this purpose a Rheolaveur washery plant was installe having a capacity of 195 tons per hour. The washed slack, clean to a 9-per-cent. ash-content, reached the consumer containing abo 5 per cent. of moisture as against 2 per cent. of moisture in the dr cleaned slack from the other colliery. Some customers, such paper-merchants, who had to keep their product absolutely clea preferred the damp fuel, but other customers in the district, such companies owning cement-works, as well as steam-raisers generall definitely preferred the dry fuel.

With regard to boilers for burning pulverized fuel, he thought was recognized that the progress of that type of boiler had be somewhat retarded by the difficulties which had arisen due to t damage caused by grit and sulphur-fumes coming from the boil chimney. At Betteshanger his company had two pulverized-fu Stirling-type boilers, each having a normal capacity of 45,000 l per hour. The boilers were equipped with short-flame burne and the fuel used consisted entirely of dust aspirated from the u cleaned coal as it travelled towards the washer. In that way a ve fine dry fuel was obtained, containing about 23 per cent. of ash, a having an average of 13·8 per cent. of volatile matter. With th material the boilers had an efficiency of from 82 to 84 per cent. Th figure was higher than the efficiency of exactly similar boilers worki with chain-grates. There had been no complaints with referen to sulphur-fumes, probably because the Betteshanger coal o contained $\frac{3}{4}$ per cent. of sulphur, but when the plant was fi started a certain amount of grit fell on the surrounding fields. T company had numerous claims on that account, and as a result th had had to instal at each of the chimneys a centrifugal grit-arres which, by removing about 78 per cent. of the grit, stopped t trouble.

Dr. G. W. ANDERSON said that he greatly admired the work of the Fuel Research Station. There was much more work going on than the Author had indicated in his Paper, but no doubt the Author had selected the most important work, namely, the cleaning and preparation of coal, and its selection for the market. Dr. Anderson felt that that work might be instrumental in providing a basis for the unification of the coal industry; such a unification was urgently needed. In any case the work would have a far wider influence on the problem of coal-utilization than on the immediate needs of the industry. No doubt those needs must be served, but it was possible to foresee vast changes taking place in the provision of fuel for the domestic hearth and for industry, because it was inconceivable that under the conditions of modern civilization solid fuel would continue to be distributed with all its attendant difficulties of transport and of disposal of the ash. Gas and electricity would, no doubt, ultimately take the place of solid fuel, even if the latter were made smokeless. The gas industry of to-day was one which showed a very high efficiency, as the thermal efficiency of gas-production was well over 80 per cent. Even so, in order to meet the future needs it would have to undergo some radical changes. As far as the gas industry was concerned, he thought that the future would show that complete gasification of coal would be essential in order to realize the changes he had outlined. Unfortunately, the processes existing to-day for the complete gasification of coal had not been very successful, for two reasons. In the first place, the gas produced was of a very low calorific value, namely, from 300 to 350 B.Th.U. per cubic foot, and it did not lend itself for general distribution. Secondly, the thermal efficiency of the processes was comparatively low, being about 60 or 65 per cent. Progress in the complete gasification of coal had been hampered by the absence of cheap oxygen, but to-day oxygen was available at a reasonable price, varying from 3*d*. to 6*d*. per thousand cubic feet, and was produced either as a by-product from the chemical industry or else by a modification of the Linde process, which had been considerably simplified. With the aid of oxygen the water-gas process, which was really the basis of complete gasification, would become a continuous one, and the loss of heat during blowing would thus be avoided. The quality of the gas was not materially changed, but if the water-gas reaction went on under pressure, carbon dioxide and methane were formed at the expense of carbon monoxide, and after removing the carbon dioxide the gas had a calorific value of the order of from 450 to 500 B.Th.U. per cubic foot, which was quite suitable for distribution. The drawback of the process was the high pressure. It had been stated that there

Dr. Anderson.

Dr. Anderson. was no need to fear high pressures; that was true, but, at the san time, if low-pressure processes were available he thought that the should be used because of the costliness of high-pressure plan The Fischer process, which was used for the synthesis of petrol i Germany, could be adapted for the enrichment of water-gas, whic then became a suitable town's-gas. By a suitable arrangement o catalysts, operating conditions and temperature, the hydrogen an carbon monoxide in the gas could react in different ways so as t produce a whole range of hydrocarbons, ranging from methane t solid paraffin. That process worked at ordinary pressures, an therefore the plant necessary for the operation was considerabl less costly than a high-pressure plant.

Whatever the future might be with regard to those two processe he felt that the question was of such vital importance that it ough to be incorporated in the programme of the Fuel Research Boar Admittedly, the Institution of Gas Engineers [1] was already attackin the problem from the point of view of the use of oxygen alone, bu he did not think the research should be stopped there. The problen was too great for any particular organization or body to undertak and required the resources of the Fuel Research Board.

Sir Clement Hindley. Sir CLEMENT HINDLEY said that The Institution regarded it as very great privilege to have received the Paper, and to have ha explained some of the work which was being done at the Fu Research Station. He had no hesitation in saying that the wor which Dr. Sinnatt, his predecessors and his colleagues had done an were doing at the Fuel Research Station had put Great Britai in the forefront of scientific work on the uses of coal. Although i was frequently said that Great Britain lagged behind in applyin scientific knowledge, such a statement would not be correct in th case of problems of coal-combustion, in which Great Britain wa leading the whole world.

He asked the members to accord to Dr. Sinnatt a very heart vote of thanks.

The vote of thanks was carried by acclamation.

The Author. The AUTHOR, in reply, observed that he was pleased to hea Sir Richard Redmayne's comments upon the general developmen which was taking place at the Fuel Research Station, and also t hear some of the early history of the Fuel Research Board, of whic the Author was a member. No completely satisfactory explanatio could be offered of the transformation which occurred in coal-sean

[1] Autumn Research Meeting, 1935.

The Author.

from one part of the field to another, until further knowledge of the constitution of coal had been obtained and combined with the accurate information which was being obtained by the Survey. There was no doubt that that knowledge, which would enable a satisfactory answer to be given to Sir Richard's question, would be of great importance, and the Survey was one direction from which the answer might come.

In reply to Dr. Lander, he wanted to make it quite clear that no attempt was made in the Paper to indicate the minimum time in which particles of coal of different types and of different degrees of fineness could be burned in air. It was well known that a great deal of work had been done by the Safety in Mines Research Board on the rate of combustion of particles of coal, and those investigations had shown that the time of combustion was very much shorter than that found by Audibert. Audibert carried out his experiments in such a way as to simulate the conditions prevailing in combustion furnaces at that time. The values were quoted because he was the originator of that line of attack, and so that the development of the grid-burner might be placed in its historical perspective.

He did not think that Dr. Armstrong was being quite fair to the Fuel Research Board in suggesting that it had not paid due attention to the gas industry. A very large proportion of the work of the Fuel Research Organization had been devoted to the study of the carbonization of coal and the treatment of the by-products. It might be added that the information being provided by the Coal Survey was of just as much importance to the gas industry as to other industries.

With reference to Mr. Bennett's remarks, it was quite true that the survey could be speeded up now that the organization was complete, but the Author would not like to follow him in his discussion as to whether research was merely a question of man-power. One of the biggest problems in connection with the Survey had been to give the staff the necessary experience to enable them to correlate the results obtained in the laboratory with those which might be expected in industry. That experience was not gained in a day. The information provided by Mr. Walsh as a result of his practical experiences in the Kent coalfield was of the greatest interest, and would prove valuable in connection with the future development of the Kent coalfield.

Dr. Anderson had mentioned the production of hydrocarbons by synthesis from mixtures of hydrogen and carbon monoxide. That problem had been studied very closely at the Fuel Research Station for a considerable time, and an intermediate-scale plant was in

The Author. course of erection there. That process was of peculiar interes because the liquid hydrocarbons formed differed markedly i character from those produced from coal by any other mean and could, for example, be treated to yield lubricating oils of goo quality. It had been recognized throughout at Greenwich that th Fischer process had further potentialities beyond the production o liquid hydrocarbons, and the possibility of adapting it to enric water-gas to the calorific value of town's gas was under consideratio

Paper No. 5050.

"Sewage-Sludge."

By Archibald Leitch, B.Sc., M. Inst. C.E.

(*Ordered by the Council to be published in abstract form only.*)

The Paper deals briefly with the methods generally adopted in the disposal of sludge, and gives the Author's estimate of the average composition of the solid constituents of sedimentation sludge as two-thirds organic matter (about half of which is in colloidal form), and one-third mineral matter, with a larger proportion of mineral matter present in chemically-precipitated sludge. It is suggested that microbes can deal only with the colloidal organic matter present, and that gas of high calorific value is generated from it. Modern digested sludge is found to contain approximately half organic and half mineral matter, so that it is a low-grade fuel, probably equivalent in thermal value to half its weight of coal. Digested sludge has practically no smell, contains no colloidal matter, dries readily, and causes no nuisance if treated in presses, centrifuges, or vacuum filters, whilst its moisture-content can be reduced to about 25 per cent. with comparatively little trouble.

Reference is made to various attempts in the past to extract the valuable constituents of sludge by the medium of heat and so to effect economy, but probably the smell nuisance due to incomplete combustion of volatile hydrocarbons proved insuperable. The results are given of an experiment, using an experimental retort at a gasworks, at a temperature of 1,250° C. to carbonize modern digested sludge. These results appeared to show that high-temperature carbonization is no more likely to be successful with digested sludge than it was in former times with undigested sludge. The gas obtained, although amounting to about 10,000 cubic feet per ton of dry sludge, is too low in calorific value (350 B.Th.U. per cubic foot) to be saleable, whilst the tar and ammonia yielded are practically valueless. It is pointed out that the coke left owing to the impossibility of gasifying all the organic matter may have some calorific value, but it contains too high a percentage of ash. The process might, however, be feasible in certain circumstances.

A laboratory experiment was then made with chemically-precipitated pressed cake in the Gray-King assay-apparatus. In carrying out the experiments, the electrically-heated drum was warmed up to 300° C., then slipped over the glass tube and the

temperature gradually raised. It was estimated that the temperature in the drum would rise to 600° C. at the end of 1 hour. All the liquor and much of the gas came off in the first 20 minutes and the gas-yield practically ceased after the first hour. The apparatus was maintained at 600° C. for a second hour but very little more gas was evolved. A temperature at or below 450° C., to which the drum would rise in ½ hour, would therefore appear to be high enough to yield all the available liquor and gas.

The experiments indicated that 12 gallons of oil of unknown value might be extracted from 1 ton (on the moisture-free basis) of Glasgow chemically-precipitated sludge pressed cake at a temperature of 450° C., leaving 14 cwts. of "coke" of fuel-value equivalent to about 4 cwts. of gas coke which could be burned without fear of any nuisance. The ash would contain the chemicals used as precipitants and any mineral fertilizers originally present in the sewage, as well as a large percentage of fine grit. Analysis would be necessary to show whether it would be most useful to farmers, plasterers or brick-manufacturers, but even if the ash could not be disposed of otherwise than by stowage at the works, its weight would only be about one-fifth of that of the original pressed cake and it would occupy less than one-fifth of the space required by the cake.

The Author estimates that 350° C. is probably sufficient to drive off the volatile constituents of the sludge, and this can readily be obtained in actual work by employing cast-iron retorts. Two-thirds of the liquor obtained was found, by distillation in a small retort, to be oil resembling bone-oil, while 70·1 per cent. of the residue in the retort was ash. The market value of bone-oil is £17 per ton, but the quantity of oil obtained from the experiments was only 6 c.c., which was too small a quantity to fractionate for valuation-purposes.

The Author appreciates that the results of large-scale experiments made at any one place may not be applicable elsewhere, because of the differences in local conditions; he submits the information contained in the Paper in the hope that it may assist authorities in charge of sewage-works, even although they may at present be discharging sludge into the sea, to determine whether it is worth while to expend money and time in investigating the economics of the subject.

NOTE.

ENGINEERING RESEARCH.

THE fifteenth Report of the Committee on the Deterioration of Structures exposed to the Action of Sea Water, which has just been published, gives a complete general account of the work done up to the present date. A brief description of the report is given below.

In the December Journal appeared a Paper on the behaviour of reinforced-concrete piles during driving, which gave the results of research carried out at the Building Research Station. The Joint Sub-Committee on Pile-Driving of the Institution Research Committee considered that the information contained therein was of such practical significance that the results should be summarized. Such a summary, with the practical suggestions arising therefrom, is given on pp. 587–92. There is also an appeal to engineers to co-operate with the Sub-Committee on Earth-Pressures in obtaining information concerning the settlement of buildings.

The series of notes on the activities of the Department of Scientific and Industrial Research is continued by a description of the activities of the Chemical Research Laboratory. In the March Journal appeared a brief account of engineering researches in progress at Sheffield University. The present number contains a description of the work at Bristol University.

The notes on research publications have been continued.

DETERIORATION OF STRUCTURES EXPOSED TO THE ACTION OF SEA WATER.

The "Sea Action" Committee of The Institution, or, to give it its full title, the "Committee on the Deterioration of Structures of Timber, Metal, and Concrete exposed to the Action of Sea Water", had its origin in July, 1916, when the Council of The Institution applied to the Advisory Committee of the Privy Council for Scientific and Industrial Research for a grant in aid of a research into the above subject under the direction of The Institution. As a result of this application, a grant was made through the Department of Scientific and Industrial Research, which allowed the work to be begun and carried on for some 7 years. For the next 5 years the Department furnished one-half of the cost, and after that the whole

of the funds needed have been provided by the generous contributions of Harbour, Dock and other Authorities in the British Isles and Dominions.

Specimens were prepared and sent to various ports where they were exposed for test and supervised by the various local Authorities at their own cost. During this period, short interim reports have been issued each year by the Committee, describing the general progress of the work. The fifteenth report which is now being issued gives a complete general account of the whole of the investigations carried out by the Committee to date.

The investigations are dealt with in the report under four main sections: I. The preservation of timber. II. The corrosion of steel and iron. III. The preservation of steel and iron. IV. The deterioration of reinforced concrete. Professor George Barger has advised the Committee throughout in regard to the timber investigations, Sir Robert Hadfield and Dr. J. Newton Friend have acted similarly in regard to steel and iron, and Dr. R. E. Stradling has dealt with the reinforced-concrete experiments.

Section I contains a detailed report by Professor Barger upon the timber investigations. Experiments were first made with various poisons, resulting in the arsenical derivative "D.M."—chlorodihydro-phenarsazine—being considered to be the most generally satisfactory. The best method of inserting the poison into the timber was found to be by means of the Bethell creosoting process, the poison being first added to the creosote. Evenness of penetration of the creosote into the timber was greatly improved by the process of incising. At first the test-pieces were exposed in home waters, but subsequently, in order to obtain more definite and rapid results, they were sent to tropical and other ports where marine borers were much more active. Specimens of local timbers which had been sent home from Australia, New Zealand and Ceylon were subjected to compression, bending and shearing tests. A detailed description of these tests and of other interesting matters is given in a report by Professor S. M. Dixon.

Section II deals with experiments in connection with the corrosion of steel and iron. The test bars were usually 24 inches × 3 inches × ½ inch and were exposed (i) above H.W. level, (2) at half-tide, (3) below L.W. level, for periods of 5, 10 and 15 years. Complete sets were sent to Auckland, Colombo, Halifax and Plymouth, whilst an additional set was sent to Plymouth for exposure in fresh water. Each set consisted of 16 bars representing rolled irons, mild and special steels and cast irons. The bars were prepared by Messrs. Hadfields, Ltd., Sheffield. They were carefully weighed before and after exposure, the loss in weight being taken as being a general

indication of the extent of the corrosion. Experiments were also made upon the effect of bringing dissimilar metals into contact and upon the effect of cold working of the bars by bending. The experiments are described in detail in a report by Dr. Newton Friend and are illustrated by numerous Tables and photographs.

Section III deals with the preservation of steel and iron by paints. Plates coated with various preservatives were exposed, some at Southampton and some at Weston-super-Mare, to aerial, half-tide and complete-immersion conditions. Plates covered with two coats of red oxide paint were adopted as a standard of comparison. Beside ordinary oxide and lead paints, the preservatives tested included bituminous mixtures and zinc galvanizing. The plates were carefully weighed before and after exposure, it being assumed that the losses in weight were roughly inversely proportional to the general protective power of the coatings. These experiments are described in detail in a report by Dr. Newton Friend.

Section IV describes experiments in connection with reinforced concrete which were carried out for the committee by Dr. Stradling, Director of the Building Research Station at Watford. These experiments were the last to be put in hand and are still incomplete. A number of reinforced-concrete piles 5 feet long × 5 inches × 5 inches were made with concretes of differing consistencies, cover and proportions and with various cements. These were exposed, some at Watford in artificial sea water, some in a tank of sea water at Sheerness and some were sent to the Gold Coast and placed in the sea. Subsidiary experiments were also made with high-alumina cement and with artificial pozzuolanas. These experiments are fully described in a report by Dr. Stradling.

The Report is published for The Institution of Civil Engineers by His Majesty's Stationery Office under the authority of the Department of Scientific and Industrial Research and copies, price 12*s*. 6*d*., may be purchased directly from H.M. Stationery Office or through any bookseller.

THE INSTITUTION RESEARCH COMMITTEE.

Joint Sub-Committee on Pile-Driving.

NOTES AND PRACTICAL SUGGESTIONS ON PILE-DRIVING.

The following notes have been drawn up as a summary of the present position of the research and an indication of the directions in which future research is necessary.

1. *The Nature of the Stresses.*—The wave-theory of the propagation of stress may be applied. The compression due to the blow travels

from the head at a velocity of about 12,200 feet per second and is reflected from the foot as a compression or a tension according to whether driving is hard or easy. The stress at any point is the sum of the stresses due to the down- and up-travelling waves. Under conditions of hard driving compressive stresses may exceed 3,000 lbs. per square inch.

2. *Head-Conditions.*—The cushion at the head of the pile, that is, the dolly and the packing in the helmet, plays an important part in determining the stresses; the softer the cushion, the lower the maximum stress. For a cushion with a linear stress—strain relation the stiffness-constant (k/A) is the stress on the pile-head to produce unit compression. Cushions usually have a non-linear stress—strain relation, and therefore k/A must be defined at "at . . . lbs. per square inch." At 3,000 lbs. per square inch values of k/A range, in practice, from 10,000 to 40,000 lbs. per square inch per inch, and at 2,000 lbs. per square inch from 6,670 to 26,700, k/A being approximately proportional to stress. Most forms of packing harden during driving. With piles of length greater than 30 feet, the maximum stress at the head is generally independent of the conditions at the foot of the pile and may be estimated from considerations of hammer weight and drop, cushion constants, and pile design and dimensions only.

3. *Foot-Conditions.*—For very easy driving conditions, that is, with very large sets, the compressive stresses at the toe will be very low and the stress-wave will be reflected as a tension, which when combined with the down-coming compression-wave produces tensions which increase from zero at the toe to a maximum towards the middle of the pile. No failures due to these tensile stresses have been observed. As resistance at the toe increases the compressive stress increases and may theoretically reach twice the value of the maximum head-stress. Values 50 per cent. greater have been recorded.

The foot-stresses depend on the total movement of the toe, that is, the set as ordinarily measured and the earth-movement at the toe. For the purpose of stress-estimation the ordinary or permanent set has been termed the "plastic" set and the earth-movement the "elastic" set. When combined, as follows, they have been called the "equivalent elastic set."

Equivalent elastic set
= twice plastic set (or permanent set as ordinarily measured)
+ elastic set (or earth-movement).

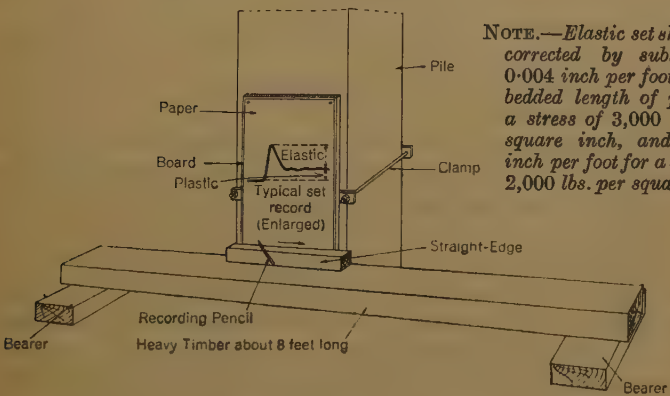
The worst conditions are obtained where the whole of the resistance to penetration is concentrated at the toe, and the theory and charts

given are based on this assumption. Friction at the sides of the pile will have only a small effect on head-stresses, but may have an important influence in reducing the stresses below ground.

4. *Measurement of Equivalent Elastic Set.*—The set-recorder has previously been described [1] and is shown in *Fig. 1* together with a typical record. A correction to the elastic set is necessary to allow for the elastic compression in the pile. This is 0·004 inch per foot of pile embedded where the maximum head-stress is 3,000 lbs. per square inch, and 0·003 where the stress is 2,000 lbs. per square inch. Further investigation of the order of the elastic and plastic sets occurring in practice is required.

5. *Estimation of Stresses.*—Charts have previously been given [2] enabling the stresses to be deduced for a wide range of conditions.

Fig. 1.



NOTE.—*Elastic set should be corrected by subtracting* 0·004 *inch per foot of embedded length of pile for a stress of* 3,000 *lbs. per square inch, and* 0·003 *inch per foot for a stress of* 2,000 *lbs. per square inch.*

SET-RECORDING APPARATUS.

A different series of charts is given with this Note, enabling any particular piling-conditions to be examined to ascertain whether maximum stresses of 3,000 lbs. per square inch or 2,000 lbs. per square inch are likely to be exceeded during driving. Three conditions of head-cushion have been included, namely, soft, medium, and hard. For all types of packing tested the hard condition has been found to apply after about 1,000 blows.

From *Fig. 2* the ratio $\frac{\text{weight of hammer and helmet}}{\text{weight of 1 foot of pile}}$ is first obtained.

From *Fig. 3* (*a*) or *3* (*b*), depending on whether 2,000 or 3,000 lbs. per

[1] W. H. Glanville, G. Grime, and W. W. Davies, "The Behaviour of Reinforced-Concrete Piles during Driving." Journal Inst. C.E., vol. 1 (1935–36), p. 150. (December 1935.)

[2] *Loc. cit.*

square inch is selected as a maximum for working conditions, the effective height of fall is then obtained for the particular conditions of head-cushion required. This effective height of fall is then converted to the height of free fall by means of *Fig. 4*. Any height of fall greater than this will produce a head-stress greater than that selected.

Figs. 3 (*a*) and *3* (*b*) also enable the equivalent elastic set which produces a similar stress at the toe, that is, either 2,000 or 3,000 lbs. per square inch, to be obtained. Equivalent elastic sets lower in value and falling below the curve produce higher stresses.

6. *Hammer-Weight in Relation to Pile-Size, Etc.*—The best conditions of driving are obtained by using the heaviest possible hammer, together with the softest head-cushion (lowest stiffness k/A), the height of drop being adjusted to give a safe stress. It is suggested that a reasonable minimum value of the ratio $\dfrac{\text{weight of hammer}}{\text{weight of 1 foot of pile}}$ would be 30. This gives for 12-inch, 14-inch, 16-inch, and 18-inch square piles hammers of $2\frac{1}{4}$, 3, $3\frac{3}{4}$, and $4\frac{3}{4}$ tons respectively (see *Fig. 2*).

In nearly all cases the equivalent elastic set increases practically in proportion to the hammer-weight, and experimental evidence shows that the plastic set (set as ordinarily measured) increases at a greater rate.

7. *Peak-Stress Indicator.*—The head-stress may be determined from the peak-stress indicator [1] which is attached to the hammer and measures its deceleration. Alternatively, the instrument may be used to indicate when any predetermined value is exceeded. Measurement of the elastic and plastic sets enables the stress-values thus determined to be used to obtain foot-stresses. The charts already given may be used for this purpose where the indicator is adjusted to 2,000 or 3,000 lbs. per square inch. Further experience of the working of the indicator in practice is necessary.

8. *Impact-Strength of Concrete and Reinforced Concrete.*—The impact-strength of concrete may be as low as 50 per cent. of the crushing-strength. For a working-stress of 3,000 lbs. per square inch a concrete of crushing-strength of not less than 6,000 lbs. per square inch is therefore necessary, and for 2,000 lbs. per square inch not less than 4,000 lbs. per square inch.

To obtain strengths greater than 6,000 lbs. per square inch proportions not leaner than $1 : 1\frac{1}{2} : 3$ (nominal), that is, 1 cwt. of cement to $1\frac{7}{8}$ cubic foot of sand and $3\frac{3}{4}$ cubic feet of coarse aggregate, should be used, and the greatest care exercised in the selection of

[1] *Loc. cit.*

aggregates, the control of water-content, and curing. (It is of interest to note that a crushing-strength of only 3,300 lbs. per square inch is required for 1 : $1\frac{1}{2}$: 3 High-Grade concrete under the Code of Practice.) For easier driving conditions, where the lower crushing-strength is adequate, that strength might be obtained by careful control with a 1 : 2 : 4 mix.

Curing-conditions have a very marked effect on impact-strength, and piles should be cured under damp conditions as long as practicable. Unless conditions of driving are easy, it is recommended that this period should be not less than 14 days. Further information is required on impact-strength and on the factors influencing it.

Longitudinal reinforcement does not affect the impact-strength greatly. The amount of lateral reinforcement, on the other hand, profoundly affects the impact-resistance of a pile, particularly at the head and toe. It is recommended that for a length from the extremities of $2\frac{1}{2}$ to 3 times the external diameter of the pile the volume of lateral reinforcement should not be less than 1 per cent. of that of the gross volume of the corresponding length of pile. The diameter of the ties should conform with the usual practice for reinforced concrete, and should be not less than $\frac{3}{16}$ inch or one-fourth of the diameter of the main bars, whichever is the greater. The minimum spacing of the ties at head and foot should be such as to provide ample facility for placing the concrete. It was observed on an outside contract that the performance of piles reinforced with heavy spirals ($2\frac{1}{4}$ per cent.) was definitely good, and although patches of surface spalling occurred, they did not materially affect the resistance of the pile to further driving.

External head-bands placed in the mould before casting the concrete considerably strengthen the pile-head.

9. *Improvements in Head-Cushion.*—To put pile-driving on a proper scientific basis an improved form of head-cushion is required possessing the qualities of permanence and of low and constant stiffness. No entirely satisfactory helmet-packing has yet been discovered, and it is possible that a mechanical device to take the place of the dolly, helmet, and packing will afford the most satisfactory solution.

10. *Necessity for Care in Details.*—The margin of safety in driving reinforced-concrete piles is frequently so low that slight carelessness in the manufacture and driving of the pile may be sufficient to cause failure. Care should be taken to restrict the water-content of the mix as far as is compatible with the production of a thoroughly dense and well-compacted concrete. The head of the pile should be carefully formed, and all surfaces in the helmet should be truly plane and at right angles to the axis of the pile. It is most important that the helmet-packing should be placed evenly on the pile-head, and

that the layer immediately in contact with the head should be of soft material covering the whole surface. The fall of the hammer should be parallel with the long axis of the pile, and the blow should be delivered as nearly concentrically as possible.

11. *Bearing-Capacity.*—The dependence of the set produced on the packing conditions indicates the importance of specifying the condition and nature of the packing to be used in determining the sets on which bearing-capacity is estimated. Failing a standard packing, it should at least be specified that the packing shall be well compacted, thus ensuring the maximum set per blow. Up to the present the research has not been concerned with the bearing-capacity of piles as such.

Method of Using Diagrams.—Given the dimensions of the pile, and the weight of hammer and helmet: to determine the maximum actual height of drop of hammer to produce either 2,000 or 3,000 lbs. per square inch maximum stress in the concrete :—

(*a*) From *Fig. 2* determine the ratio

$$\frac{\text{weight of hammer and helmet}}{\text{weight of 1 foot of pile}}$$

(*b*) From *Fig. 3* (*a*) for 2,000 lbs. per square inch maximum stress, or *3* (*b*) for 3,000 lbs. per square inch, determine the maximum effective height of fall for the appropriate cushion (the hard cushion and therefore the highest value of k/A applies after about 1,000 blows).

(*c*) From *Fig. 4* determine the height of free fall for the appropriate ratio $\dfrac{\text{weight of helmet}}{\text{weight of hammer}}$.

(*d*) To obtain the actual height of drop, divide this value by 0·8 for a winch-operated drop-hammer, or 0·92 for a single-acting steam-hammer.

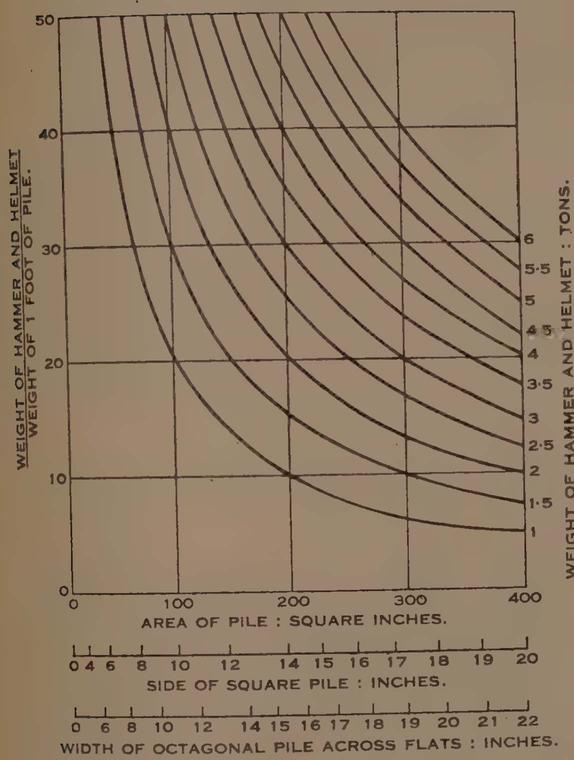
(*e*) From *Fig. 3* (*a*) or *3* (*b*) determine the minimum equivalent elastic set (see *Fig. 1*) to produce a foot-stress of 2,000 or 3,000 lbs. per square inch respectively.

Sub-Committee on Earth-Pressure.

Settlements of Buildings.

The Sub-Committee on Earth-Pressures of the Research Committee of The Institution wish to enlist the co-operation of engineers in obtaining data on the settlements of buildings in connection with the research in hand at the Building Research Station. The main object of this aspect of the research is to correlate results of laboratory

Fig. 2.



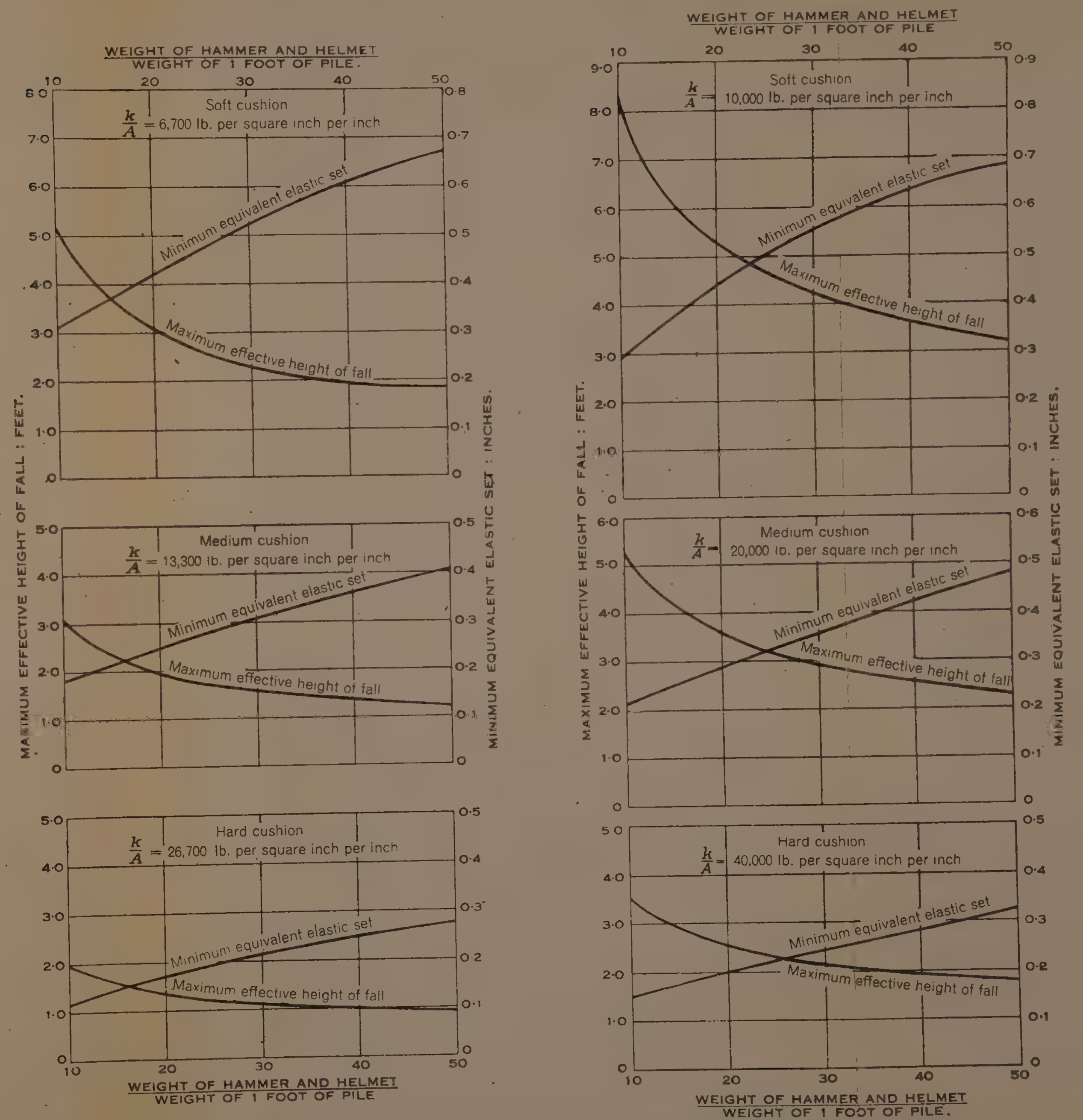
NOTE.—*Helmet weights range from 3 to 10 cwt., 5 cwt. being usual.*

DIAGRAM GIVING THE RATIO $\dfrac{\text{WEIGHT OF HAMMER AND HELMET}}{\text{WEIGHT OF 1 FOOT OF PILE}}$ FOR A RANGE OF PILE-SIZES AND HAMMER-WEIGHTS. (Weight of reinforced concrete taken as 160 lbs. per cubic foot.)

Figs. 3.

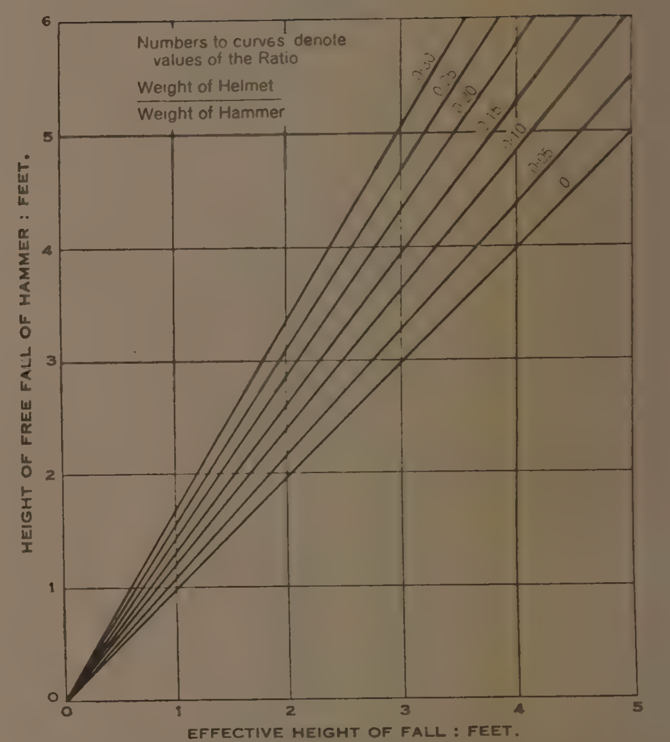
(*a*) FOR MAXIMUM STRESS OF 2,000 LBS. PER SQUARE INCH.

(*b*) FOR MAXIMUM STRESS OF 3,000 LBS. PER SQUARE INCH.



RELATION BETWEEN THE RATIO $\dfrac{\text{WEIGHT OF HAMMER AND HELMET}}{\text{WEIGHT OF 1 FOOT OF PILE}}$ AND THE EFFECTIVE HEIGHT OF FALL AND MINIMUM EQUIVALENT SET FOR A GIVEN MAXIMUM STRESS IN THE PILE. ($2\frac{1}{2}$ per cent. longitudinal reinforcement in pile. Young's Modulus for concrete $4{\cdot}5 \times 10^6$ lbs. per square inch.)

Fig. 4.



NOTE.—*No allowance has been made for frictional loss in hammer-guides. Usual allowances are :—*

For winch-operated drop-hammer, equivalent height of free fall=80 per cent. of actual fall.

For single-acting steam-hammer, equivalent height of free fall=92 per cent. of actual fall.

CONVERSION OF EFFECTIVE HEIGHT OF FALL TO HEIGHT OF FREE FALL OF HAMMER FOR VARIOUS RATIOS $\dfrac{\text{WEIGHT OF HELMET}}{\text{WEIGHT OF HAMMER}}$.

tests on samples of soil with settlements observed in practice, and thus to determine safe bearing-pressures. In connection with each structure selected for observation, samples will be taken of the soil. Mechanical tests of these will be made in the laboratory and observations of settlements made both during and after construction.

In order to arrive at any satisfactory conclusions, it will be necessary for observations to be made on a large number of buildings from the commencement of building. The amount of work involved is beyond the capacity of the research staff and it is felt that the co-operation of engineers in a position to take occasional observations over a period of years on particular buildings would considerably expedite the collection of a useful amount of information. The Building Research Station will undertake the soil-sampling, carry out laboratory tests and provide particulars of the methods of making the measurements.

The Sub-Committee would be grateful if engineers in a position to assist would communicate either with the Secretary of The Institution or the Building Research Station direct.

WORK OF THE CHEMICAL RESEARCH LABORATORY.

Corrosion of Metals.

The mechanism of corrosion (principally of mild steel), both in immersed conditions and under atmospheric exposure, is being studied, together with certain technical problems including the protection of magnesium alloys from corrosion by sea-water and from attack by aircraft fuels. The production of artificial patinas on copper and bronze used in architecture and sculpture, and the corrosion of locomotive boiler-tubes are also subjects of investigation.

The more fundamental work is carried out in relatively simple, constant, strictly-defined and reproducible conditions, and is directed toward the discovery of the respective corrosion-factors. As such knowledge accumulates, the results of field and industrial tests are expected to become easier to interpret; in certain cases they may even become predictable.

Special techniques have been developed for following accurately the progress of corrosion over long periods. Immersed conditions of corrosion include both stagnant and moving water and salt solutions under ordinary and high pressures. Corrosion corresponding with hydrogen-evolution and oxygen-absorption can be distinguished and measured. The corrosion of metals exposed to standard atmospheres is conducted under controllable conditions as regards gaseous constituents, relative humidity and temperature.

High-Pressure Research.

The study of catalytic reactions with carbon monoxide and hydrogen under high pressure was begun at Teddington in 1926 with the object of acquiring the technique of high-pressure research. Condensations with carbon monoxide and hydrogen (water-gas) were examined, when it was seen that modifications of the catalyst led to variation in the methanol product; thus, whilst the addition of strong alkali favoured the formation of higher alcohols, the incorporation of cobalt led to a synthesis of notable amounts of ethyl alcohol.

Polymerization of ethylene under conditions of high temperature and pressure gave rise to a complex mixture of saturated, unsaturated and benzenoid hydrocarbons, various fractions of which were suitable as fuel for internal combustion engines.

Experiments on the synthesis of acetic acid from carbon monoxide and methanol under pressure, in the presence of a catalyst consisting of phosphoric acid with a small amount of copper phosphate, have shown it possible to obtain an 80-per-cent. yield of acetic acid calculated on the methanol consumed. This type of synthesis has been applied to the production of other organic acids from higher alcohols and olefines.

Tar Research.

Systematic investigation of low-temperature tar has shown that this novel product of coal differs considerably from the better known high-temperature tars. The neutral oils are of paraffinoid character, whilst the phenolic content may amount to 25 or 30 per cent. of the tar, the remainder of the tar consisting of several chemical varieties of resinoids. Solid aromatic hydrocarbons are present only in traces and consist largely of methylated derivatives of naphthalene, anthracene and naphthacene. The most volatile phenols contain carbolic acid, the three cresols and five of the six possible xylenols.

Investigations are proceeding on the constitution of the higher tar-acids. These compounds, which are powerful germicides, have been put to industrial use as a wetting agent in the textile industry. The problem of the cause and prevention of corrosion of tar-stills is receiving attention and it has been shown that in addition to ammonium chloride, the resinoid portion of tars is an active destructive agent at temperatures of about 300° C.

Tars have been incorporated with rubber and rubber derivatives in an attempt to improve these oils as road-surfacing materials. Rubber is compatible with low-temperature and vertical-retort tars but not with horizontal-retort or coke-oven tars, whilst chlorinated

rubber dissolves more easily in high-aromatic tars than in vertical-retort or low-temperature tars.

Chemotherapy Section.

This section directs its attention to the preparation of substances which are likely to be of utility in the treatment of trypanosomiasis (African Sleeping Sickness) and other protozoal diseases, the main object of all such investigations being the discovery of new drugs which will either supplement or supersede existing remedies. One series of compounds is giving very promising results. They have all been derived from Atoxyl, an arsenical drug recognised as a basis of treatment of sleeping sickness, and they have shown considerable curative activity in experimental trypanosomiasis and more recently in clinical trials.

Synthetic Resins.

Phenolic-formaldehyde resins have been investigated primarily for improvements in electrical and mechanical properties. They have been examined as moulding mixtures, using various fibrous "fillers" as resin-forming agents, and also in the form of laminated material, which consists essentially of porous sheet material bonded together with resin under heat and pressure. Chemical plant and electrical apparatus of all kinds are among the many applications of these resins; laminated products are employed in panelling. A cheap substitute for pure phenolic resins has been obtained by the condensation of formaldehyde with low-temperature tar-fractions; the products are of interest where cheapness is of primary importance. Theoretical considerations have also been developed.

From ketone-formaldehyde condensations a material has been developed, simulating glass, but so much less brittle that it can be readily machined or turned.

Insoluble condensation-products of formaldehyde with certain polyhydric phenols, including tannins, and bases have been shown to possess the property of adsorbing both cations and acids from solution. The advantages of softening as well as purifying water by such methods are noteworthy.

Water-Pollution Section.

An investigation of the base-exchange process of water-softening (in which the calcium and magnesium of a hard water are replaced by sodium) has shown that satisfactory materials can be produced from clays of British origin and also from certain types of synthetic resins. Some drinking-water, which is otherwise suitable, acts upon

lead piping used to convey it to the consumers unless it has been previously treated. A summary of information available at present has been issued.[1] Work is at present concerned with the theoretical aspect of the corrosion of the metal and with improvements in methods of estimating the lead-content of drinking-water under practical conditions over long periods of time.

Road Tar Section.

The physical and chemical properties of tar are being studied, on behalf of the British Road Tar Association and in collaboration with the Road Research Laboratory, to determine how far these affect the behaviour of tar when used as a road-material, and to discover in what directions improvement in road-tar may be effected. Viscosity, the most notable property, is measured in absolute units and is regarded as a standard to which other measurements, chemical or physical, are referred. The laws governing variations of viscosity brought about by temperature, thixotropy, oil-content, chemical action and suspended solids are being closely examined.

The ageing of tar is receiving attention and attempts are being made to devise an accelerated weathering test. This involves detailed comparison of the effects of artificial and natural conditions. Viscosity-changes produced by outdoor exposure are greater than can be accounted for by assuming that evaporation of oil is the only factor involved; oxidation and polymerization accelerated by light help to augment the viscosity particularly in the surface layers of tar.

Micro-biological Section.

Among the activities of the micro-biological section attention may be drawn to the work carried out there on certain bacteria which reduce sulphates to sulphides. These bacteria have been found to be widely distributed in nature in places where air does not penetrate, for instance, in clayey soils, in river and sea mud, and in bogs. Evidence has been collected to show that the sulphate-reducing bacteria may be a factor in the corrosion of metals which are buried in clay, in sea or river mud, or in bogs. Cast-iron or steel pipe-lines, for instance, for the conveyance of water-supplies are often found to corrode prematurely when buried in clay, a corrosion which leads to the formation of an excessive amount of iron sulphide in the corrosion-products.

The harmful activity of the sulphate-reducing bacteria has also been detected in the water "floors" of gas-holders, where it results in the contamination of the gas with undesirable volatile sulphur

[1] Water Pollution Research Board No. 4, H.M. Stationery Office, 1934.

compounds, and in paints, where it may be the cause of discoloration of painted surfaces.

The Less Common Metals.

Certain coal ashes and flue dusts contain small quantities of the rare metals germanium and gallium. Many such materials have been examined and methods have been devised for extracting these elements on a semi-technical scale. The rhenium content of Australian molybdenite has also been investigated and some work done on the chemistry of this element.

Fundamental research on the complex salts of the currency metals (copper, silver and gold), nickel, iron, cobalt, platinum, ruthenium, and osmium has been in progress for some years. Promising results in the treatment of bovine tuberculosis have been obtained with certain of the gold derivatives, and these are now being tested clinically. The dehydrogenation of pyridine under pressure by means of metallic chlorides, such as dry ferric chloride, has furnished many interesting bases, notably $2:2'$ dipyridyl and $2:2':2''$ tripyridyl which have been used for the detection and colorimetric estimation of ferrous iron in sea water and other products. The organic chemistry of selenium and tellurium has been extended to the preparation of many new cyclic derivatives.

Derivatives of Diphenyl.

The large-scale oxidation in America of benzenoid to poly-nuclear hydrocarbons has furnished new intermediates and valuable boiler fluids. From diphenyl itself are derived benzidine, diphenyline, carbazole and aminocarbazole, and also the hitherto almost inaccessible phenanthridines, the application of which for dyestuffs and drugs (particularly antiseptics) has been examined.

Chemical Engineering.

The laboratory has two well-equipped workshops with a staff of six mechanics, and a drawing office for the design, construction, and maintenance of apparatus needed by the various sections of research. In addition, the laboratory is equipped for semi-scale researches on coal-tar products and synthetic resins, the plant installed including filter presses, vacuum ovens, jacketed pans and stills, incorporating-machines and extractors. All sections of the laboratory are provided with compressed-air, steam and vacuum services. A section of the laboratory has been fitted with apparatus and plant for conducting experiments at pressures up to 200 atmospheres at temperatures up to 450° C. and a special plant has also been built for experiments at pressures up to 3,000 atmospheres at temperatures not greater than

240° C. For batch experiments at high pressures, the laboratory has a battery of nine gas-heated autoclaves ranging from 25 c.c. to 1,400 c.c. working capacity, all of which have been constructed in the workshops. The equipment also includes 5- and 4-stage gas-compressors and storage for gases up to 500 atmospheres.

RESEARCH WORK IN ENGINEERING AT BRISTOL UNIVERSITY. (March, 1936.)

Researches covering a diverse range of subjects are being carried out at the Merchant Venturers' Technical College in which the Faculty of Engineering of the University of Bristol is conducted. They may conveniently be considered under the headings of the three main departments: Civil, Mechanical and Electrical Engineering.

Civil Engineering Department.

First and foremost in magnitude and importance is the work of the Steel Structures Research Committee of the Department of Scientific and Industrial Research. Commenced in 1929 at the Building Research Station, the work was taken to Bristol by Professor J. F. Baker on his appointment to the chair of Civil Engineering. The work is now finishing and the report is in course of preparation. The stress-distribution in three actual buildings has been investigated during construction, and as a result of these and other investigations it has been possible to draft rules governing the design of steel-frame buildings which are rational and must produce a sound and more economical structure. The results are being embodied in a final report to be published shortly and are summarized in the paper, "The Rational Design of Steel Building-Frames," to be read before The Institution on the 21st April. A subsidiary research in connection with this work is on the effect of skew connections on stanchions.

An unusual aspect of structural research is a study of the behaviour of structures during earthquakes. A steel frame suitably loaded to represent the masses of walls and floors forms a model of a building. This is mounted on a base to which various periodic motions can be imparted and the reaction of the building is studied by optical deflectometers.

A scale model of a stiffened suspension bridge is being used to verify refinements in the theoretical treatment.

Hydraulic research is represented by a determination by means

of a scale model in plaster of the most suitable form for the spillway and overflow channel of the lower Sherbourne Reservoir (Bristol Waterworks Company) which are being modified to comply with the provisions of the Reservoirs Safety Act.

The equipment includes the following testing machines :—

50-ton Buckton testing machine.
50-ton Denison ,, ,,
10-ton Denison ,, ,,
10,000-lbs. Denison testing machine.
Avery torsion testing machine.
Shore Scleroscope.
Sankey bending machine.
Bailey cement tester, etc.

Mechanical Engineering Department.

A fundamental research on the criterion of failure of tubes under static torsion has been in progress for several years. The first part of this research dealing with thin tubes has been satisfactorily completed. After great initial difficulties due to lack of uniformity in the material, it was found that consistent results could be obtained with untreated mild steel. The theory of Donnell on elastic instability in torsion was confirmed. The behaviour of thick tubes and solid shafts, in which inelastic deformation cannot be ignored, is a more complex problem and a definite criterion of failure in such tubes of mild steel has not yet been obtained.

A research has also been carried out on the effect of the rate of straining in a tensile test on the yield and the ultimate stress in tension.

Electrical Engineering Department.

An extensive theoretical and experimental investigation on the whirling of shafts has been and is still being carried out. Papers [1]

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[1] David Robertson, "Vector Methods of Studying Mechanical Vibrations," *The Engineer*, vol. cli (1931, Part 1), pp. 230, 256, 288, 314.
"Static Balance of a Shaft with Skew Stiffness," *The Engineer*, vol. cliv (1932, Part 2), p. 126.
"Whirling of a Journal in a Sleeve Bearing," *Phil. Mag.*, Ser. 7, vol. 15 (1933), p. 113.
"Whirling of a Shaft with Skew Stiffness," *The Engineer*, vol. clvi (1933), pp. 152, 179, 213.
"The Whirling of Shafts," *The Engineer*, vol. clviii (1934), pp. 216, 228.
"Transient Whirling of a Rotor," *Phil. Mag.*, Ser. 7, vol. 20 (1935), p. 793.
"Subsidiary Whirling of Rotors due to Speed Oscillation," *Phil. Mag.*, Ser. 7, vol. 21 (1936), p. 474.
"Hysteretic Influences on the Whirling of Rotors," Minutes of Proceedings Inst. Mech. E., vol. 131 (1935).

have been published on static balance, transient whirls, effects of skew stiffness, hysteretic effects, speed oscillations, and on journal whirling. A research on the influence of the bearings on whirling is in progress. Numerous errors in accepted theory have been discovered in the course of these researches.

A research on clocks and time-keeping has been in progress for many years and is still proceeding. The theory of pendulums and escapements has been studied and several new forms have been devised. Methods of comparing the frequency of stroboscopic vibrators with a standard clock for accurate measurements in short-time tests have been evolved and improvements are being attempted.

The discovery that a steel tensile test specimen during testing becomes magnetized has led to a study of the magnetic field during the application of load. No matter what the initial state of magnetization the final direction of the magnetization conforms with the external magnetic field. So marked is the effect on the flux that a study of the change of flux was suggested as an accurate means of determination of the true elastic limit of steel or iron. Even at very early loadings, sudden changes in flux indicate the occurrence of creep. Under a constant load, variations in permeability indicate that creep takes place over several days before stability is reached. This research promises to provide a new technique in the study of ferrous metals. In the course of the above investigation it became necessary to develop a recording extensometer of high sensitivity.[1] A method employing a change of electrical capacity with length has been used, the variations in electrical current so caused being amplified sufficiently to operate a direct-writing moving-iron oscillograph or a cathode-ray oscillograph.

The above researches are being carried out under the direction of Prof. A. Robertson, D.Sc., M. Inst. C.E., M. I. Mech. E., Dean of the Faculty of Engineering and Professor of Mechanical Engineering, Professor J. F. Baker, M.A., D.Sc., Assoc. M. Inst. C.E., Professor of Civil Engineering, and Professor D. Robertson, D.Sc., M.I.E.E., Professor of Electrical Engineering.

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[1] "An Electrical Recording Extensometer," *Engineering*, cxxxvi (1933), p. 699; "An Application of the Thermionic Valve to the Measurement of Physical Quantities," Journ. Sci. Insts., vol. 12 (1935), p. 192.

NOTES ON RESEARCH PUBLICATIONS.

Published researches in connection with measuring instruments include a description in the *Trans. Inst. Mining Engrs.*, **90,** *259*, of a method of geophysical surveying with an oscillating magnetic needle. The applications of the stroboscope in engineering research are enumerated in *Mémoires Soc. Ing. Civ. Fr.*, **88,** *581*. An experimental investigation of manometer errors due to capillarity is described in *Instruments, The Magazine of Measurement and Control*, **9,** *36*.

Among the researches on the properties of engineering materials may be noted the following. An investigation into the principle rots of English oak is dealt with in a paper issued from the Forest Products Research Laboratory. The increase of strength and hardening with age of various cement concretes is described in *Bulletin Téchnique de la Suisse Romande*, **62,** *53*. The contribution to the study of the vibration of concrete of the Building and Public Works Laboratories is described in a new publication: *Annales de l'Institut Technique du Bâtiment et des Travaux Publics* **1,** *18*. The effect of the coarse aggregate and other factors such as the time of mixing and subsequent wet storage, the setting time of the cement, etc., on the properties of concrete has been investigated at Birmingham University and forms the subject of an article in the *Structural Engineer*, **14,** *131*. Tests on the bond strength of "Isteg" steel reinforcement are given in the *Engineer*, **160,** *521*. The relation of the soluble salt-content to florescence in bricks is discussed in *British Clay*, **44,** *271–4*. Research at Leeds University on the elasticity and plasticity of rocks and artificial stone is described in *Proceedings, Leeds Philosophical and Literary Soc.*, **3,** *145*. The relation between breaking stress and mean principal stress in brittle materials is dealt with in *Travaux, Feb. 1936, 78*. An experimental

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The figure in heavy type is the number of the Volume; the figure in brackets the number of the Part; and that in italic type the number of the Page.

determination of the torsional stress-strain diagram at constant speed of deformation and the influence of the speed upon the shape of the diagram is given in *De Ingenieur* (*Werktuig en Scheepsbouw*), **51,** *23–29.* In torsion strain is not proportional to the radius beyond the elastic limit. A method is given of evaluating the relation between strain and turning-moment at various rates of twist. The importance of friction-oxidation in fatigue-failure is discussed in *Zeit. Metall.*, **27,** *277–280.* "The effect of initial compressive stress upon the fatigue-strength of metals" by G. Seeger (*V.D.I. Verlag, Berlin, 1935*) gives the results of an extensive series of tests carried out at the Technical College, Stuttgart, and shows that the fatigue strength of brittle and hard materials is increased, but in materials of medium hardness may be diminished by initial compression. By the same publishers is "The effect of stress on the plasticity of metals," by A. F. Maier. A mathematical analysis for the determination of stresses in a metal by X-ray diffraction is presented in *Physics* **7,** *1–8.* The addition of copper to mild steels is shown greatly to increase their resistance to atmospheric corrosion in *Copper Development Association Engineers' Note Book Series, No. 4, London, 1935.* The behaviour of stationary wire ropes in tension and bending, including the effect of different steels, regular or Lang lay, preformed or non-preformed types, is discussed in *Proc. Am. Soc. Civ. Engineers*, **62,** (*2*). A comparison of various formulas for strength is given and a bibliography appended. A study of the properties and resistance to corrosion of cadmium plating is given in the *Jnl. Am. Soc. Naval Engineers*, **48,** *59.* *Revue de Métallurgie*, **9,** *393–7*, gives the results of tensile tests of anti-friction alloys at high temperatures. The relation between plastic deformation and the hardness of lead is dealt with in *Académie des Sciences, Comptes Rendus*, **202,** *222.* *Zeitschrift für Metallkunde*, **27,** *281–5*, publishes an article on the hydrogen-permeability of copper, iron, nickel, aluminium and some of their alloys. A paper on the applications of light alloys in general engineering design (*Trans. Inst. Engineers and Shipbuilders in Scotland*, **79,** *238*) summarises the progress in the development of alloys of aluminium and magnesium.

The production and manufacture of materials is considered in the following articles. The permeability of mortar and concrete to oils is dealt with in *Génie Civil*, **107,** *563–6.* A study of the uniformity of concrete on the average job based on 13,000 field tests is given in the *Jnl. Am. Concrete Inst.*, **7,** *277.* In the same journal is given a method for determining the air content of freshly-mixed mortars and concretes and a description of the latest American developments in the technique of delivering concrete by pump and pipe line.

A survey of the history and characteristics of stainless steels now available is given in the *Journal Inst. Production Engineers*, **15,** *47*.

The following research is being carried out in connection with mass structures: Studies of the physical and mechanical characteristics of soils carried out at the Laboratoires du Sol et des Fondations, 1935, are described in *Annales de l'Institut Technique du Bâtiment et des Travaux Publics*, **1,** *64*; and in the same journal, p. *13*, is an article on stability of earthworks. Mathematical analysis of foundation pressures taking into account flexure of the foundation is described in *Revue Universelle des Mines* (*Liége*), **12,** *94*. The characteristics of cohesionless soils affecting the stability of slopes and earth fills are discussed in the *Journal of the Boston Soc. Civ. Engineers*, **23** (*1*). When a cohesionless soil is in its densest state the grains are interlocked and movement cannot take place without increase of volume. Shearing forces produce a continuous increase in volume until a critical density is reached at which sliding can take place and beyond which no further increase in volume takes place. In this article the importance of compacting cohesionless soil in embankments and particularly in dams so that the density is greater than the critical density is emphasized and vibration methods of compacting are advocated. The danger of slipping of earth and the stability of foundations is also dealt with in *Annali dei Lavori Pubblici*, **74** (*1*) *21*. The flow through the ground under a pressure-gradient of water carrying fine sandy and clayey particles is treated mathematically in *Trans. Scientific Research Inst. of Hydrotechnics, Leningrad*, **15.** The process of silting up of the soil structure is expressed by means of finite functions and the results have been checked experimentally. In the same journal is given a method of studying the percolation of ground water as a three-dimensional problem by means of electro-hydrodynamical analogy. The seepage of water through dams with vertical faces is dealt with in *Physics*, **6,** *402–15*. A solution of water seepage problems by electrical conduction through models is also dealt with in the same journal, pp. *395–401*. An investigation of the occurrence of cracking in pre-cast reinforced concrete piles caused by steam pile-driving is given in *Annales des Travaux Publics de Belgique*, **36,** *9–36*. High test results obtained with short piles cast in situ are given in *Engineering News-Record*, **115,** *842–4*. In an article on the deterioration of buildings of the Middle Ages in *Annales de l'Institut Technique du Bâtiment et des Travaux Publics*, **1,** *1*, an attempt is made to analyse the causes of deterioration. Research on stone-masonry is described in *Autobahn, 1935*, **2,** *810–16*. A solution of complicated stress-distribution

by means of model experiments is given in the *Jnl. Inst. Engrs. Australia*, **7,** *345–54.*

Dealing with framed structures: in the *Proc. Royal Society, Series A*, **154,** *4*, is a paper on Castigliano's principle of minimum strain energy. A mathematical study of steady forced vibrations of single mass systems with symmetrical as well as unsymmetrical non-linear restoring elements is given in the *Jnl. Franklin Inst.*, **220,** *467–96.* A book on the buckling of unsupported angles stressed in compression by C. Kollbrunner is published by *Leeman* (*Zurich and Leipzig*), *1935.* A second article on the action of wind on buildings and constructions dealing particularly with cylindrical surfaces and lattice girders, etc., appears in *Travaux, Feb. 1936, 71.* Formulas developed from test results at the University of Illinois on welded structure design for dynamic loads are given in *Eng. News-Record*, **116,** *310.* In *Stahlbau*, **9,** *3–7*, tests are given on the bearing capacity of welded girders subjected to plastic deformation under repeated loading. Cracks in reinforced concrete are dealt with in *Génie Civil*, **108,** *182*, and the stress-distribution of reinforced-concrete beams according to experiments at Leeds University in *Structural Engineer*, **14,** *118.* Proposed specifications for reinforced concrete are dealt with in: a paper on slabs supported on four sides (*Jnl. Am. Concrete Inst.*, **7,** *350*), draft standard specification for the design and execution of reinforced concrete floors (*Austrian Standards Committee: Sparwirt.* **13,** *352–6*), and the new Austrian specification for reinforced concrete (*Öst. Ing. Arch. Ver.*, **87,** *175–6*). The influence of the plasticity of concrete on the design of reinforced concrete sections under eccentric compression is dealt with in *Beton und Eisen*, **34,** *335–8.* Research on the value of prestressing reinforcement in reinforced concrete is described in *Mémoires Soc. Ing. Civ. Fr.*, **88,** *643.* In the *Jnl. Franklin Inst.*, **220,** *754*, is an article on the waterproofing of concrete structures. Bending stresses in a cylindrical reinforced-concrete tank with domed roof monolithic with the tank wall are calculated in *Bauing.*, **16,** *329–30.*

Research on heat engines includes: *Technical Paper No. 42. Fuel Research Station of the D.S.I.R.*, "The action of hydrogen upon coal, Part 2. Early experiments with the Bergius Process," in which the evolution of the process of the production of oil from coal is described. Further work carried out at the Fuel Research Station on colloidal fuel is described in a paper read before the Inst. Chem. Engineers 21 Feb. 1936. A study of the frequency of vibration due to the ignition of the charge in internal combustion engines is given in *Comptes Rendus des Séances de l'Académie des Sciences*, **202,** *631.* Research on friction and leakage past piston rings carried out at

Armstrong College is described in the *N.E. Coast Inst. Engineers and Shipbuilders, Transactions*, **52**, *143*.

The following electrical researches are described in the *Inst. Electrical Engineers Jnl.*, **78**: *p. 257*, Standardization of impulse-voltage testing ; *p. 317*, Neutral inversion in power systems ; *p. 326*, Fluctuation noise in vacuum tubes which are not temperature-limited. In an article on the internal energy of ferro-magnetics (*Philosophical Trans. Royal Soc. of London*, **235**, *165*) an analysis is made of experimental data to derive information on the dependence of the internal energy of ferromagnetics on intrinsic magnetization and temperature.

Research on mechanical processes and apparatus includes the following articles on welding in the *Am. Weld. Soc. Jnl.*, **15**: *p. 6*, Welding of the alloy steels ; *p. 14*, Welding and cutting high chromium steels ; *p. 18*, Yoloy—its properties and welding, a description of a new alloy particularly suitable for welding ; *p. 23*, Arc welding in argon gas, a report on research work at Lehigh University ; *p. 28*, Tests to determine the feasibility of welding the steel frames of buildings for complete continuity. Experiments on the exit velocity and slip coefficient of flow at the outlet of a centrifugal pump impeller and their relation to the characteristics of a pump are dealt with in *Memoirs of the Faculty of Engineering, Kyushu Imperial Univ., Japan*, **8**, *1*. In connection with research on lubrication, a study of the seizure of various combinations of metallic surfaces at elevated temperatures and the methods of testing for propensity to seizure are discussed in *Mechanical Engineering*, **58**, *165*. In *Mémoires Soc. Ing. Civ. Fr.*, **88**, *623*, is an article on the need to distinguish and measure the effect of " greasiness " as against simple viscosity in considering the friction of bearings, and on *p. 632* is a suggested method of studying friction by means of the electro-magnetic analogy of the fields of force round molecules.

The following researches relate to roads :—The structural design of concrete pavements is dealt with in *Public Roads*, **16**, *145–8* and *169–97*, wherein the effects of temperature and moisture are studied. It is shown that the thickening of the edge of a long slab increases the maximum tensile stress and may actually decrease the load-carrying capacity, but the strength of corners is increased. In the summaries of papers and reports of the *15th Annual Meeting of the U.S. Highway Research Board, 1935, p. 3*, are papers on the stresses in concrete pavement slabs and on tests of concrete pavement joints. Concrete slabs reinforced with welded wire fabrics are considered in *Am. Concrete Inst. J.*, **7**, *219–27*. The designation of bitumens used in road making on the basis of their absolute viscosities and a descrip-

tion of a new and simple practical method of test are discussed in *Bulletin No. 101 of the Permanent International Association of Road Congresses, Sept.–Oct. 1935.*

Researches dealing with water transport, canals and rivers: a mathematical study of wave motion in a rectangular channel following Bénard-Kármán is given in *Comptes Rendus des Séances de l'Académie des Sciences*, **202,** *629.* In the *Proc. Am. Soc. Civ. Engineers*, **62,** (*2*), the backwater function is evaluated and tabulated for calculation of varied-flow in open channels of adverse slope. An experimental study of the flow past rectangular recesses of various dimensions is given in *Bauingenieur*, **17,** *55.* In the *Trans. Scientific Research Inst. Hydrotechnics, Leningrad*, **15,** the hydraulic design of sluice openings as affecting silt-laden rivers is considered mathematically. In the same journal is an experimental investigation of the accuracy of the elutriation scales used in grain-size distribution analyses. The time required for sedimentation according to size and shape of the particles is given for quartz grains and is compared with Stokes' formula for spherical grains. A paper on the wake and thrust deduction of single-screw ships in which the losses due to wake in model and full-scale tests are compared is given in *Trans. N.E. Coast Inst. Engineers and Shipbuilders*, **52,** *179.* In the *Am. Soc. Naval Engineers Journal*, **48,** *19*, a method of estimating the wind resistance of ships is given.

In connection with aeronautical research: the experimental investigation of the interference of solid bodies in a stream of fluid, giving an analysis of the pressure distribution on spheres and cylinders in an air stream as affected by their mutual proximity, is given in *Trans. Scientific Research Inst. Hydrotechnics, Leningrad*, **15,** *1935.* The Bréguet gyroplane, a development of the gyroplane in which the efficiency is increased by imparting an undulatory motion to the wings, is described in *La Technique Moderne*, **28,** *149.* *The National Advisory Committee for Aeronautics* (*U.S.A.*) have published the following reports, 1935: *No. 528*, Reduction of hinge-moments of air-plane control-surfaces by tabs; *No. 530*, Characteristics of the N.A.C.A. 23012 air-foil from tests in the full-scale and variable-density tunnels; *No. 534*, Aerodynamic characteristics of a wing with Fowler flaps including flap-loads, downwash, and calculated effect of take-off; *No. 543*, Tank tests of N.A.C.A. model 40 series of hulls for small flying boats and amphibians; *No. 544*, Combustion in a bomb with a fuel-injection system; *No. 546*, The effect of turbulence on the drag of flat plates. A report on flexural and shear-deflection of metal spars is given in *Aeronaut. Res. Comm. Reports and Memoranda, No. 1671.*

Research on hydraulics and sewerage includes the following theoretical investigations:—In the *Cambridge Philosophical Soc. Proc.* **32,** *40,* the stability of viscous fluid flow under pressure between parallel planes; *p. 55,* on the stability problem in hydrodynamics; *p. 67,* the gliding of a plate on a stream of finite depth. In the *Trans. Scientific Research Inst. Hydrotechnics, Leningrad,* **15** (*1935*), a mathematical determination of the length of a hydraulic jump is made by considering the flow as divided into a dead zone of elliptical shape, where rotation only occurs, and a region of progressive flow. In the same journal a hydromechanical analysis of run-off is developed by forming a general differential equation in curvilinear co-ordinates in which the contour lines and lines of flow are chosen as the x and y co-ordinates respectively. By this means the flow of rainwater from any arbitrary surface can be determined. A graphical solution is given for the case in which the difference between precipitation and losses can be represented as a function of time only. Research carried out at the Thermotechnical Institute, Moscow, on the evaporation from a free water surface is described in *Industrial and Engineering Chemistry* (*U.S.A.*), **28,** *345.* A description and figures relating to various methods of storage of energy by pumping in connection with hydroelectric installations are given in *Annales des Ponts et Chaussées, Dec. 1935, 845.* In the *Annual Report of the Liverpool Observatory and Tidal Inst., 1935,* researches on tides, the bore of the Trent and the coefficient of friction in the Bristol Channel are given. An article on the effect of sewage gases on concrete is given in *Clay Products J. Aust.,* **3,** *11–12.*

On the subject of mines research a description of laboratory tests on cogs in which full-size cogs both filled with stone and unfilled were tested to failure at the Imperial College of Science is given in the *Proc. S. Wales Inst. Engineers,* **52** (*1*).

Research on lighting, heating and ventilation: *D.S.I.R. Illumination Research Technical Paper No. 18,* describes research on the transmission of light through glass windows with different glasses, different kinds of surfaces, and different patterns and colours, and investigates the clearness, concealing power and rate of dirtying, etc. in the various cases. The measurement and significance of visibility is discussed in the *Franklin Institute Jnl.,* **220,** *431–6,* and large-scale laboratory studies of various types of illumination, of glare and of the optimum distribution in connection with highway lighting are dealt with in *Trans. Illuminating Engg. Soc.,* **31,** *103.* The second edition of *D.S.I.R. Building Res. Tech. Paper No. 13,* "The Equivalent Temperature of a Room and its Measurement" has appeared. Heat insulation in buildings is discussed in *Merkblatt No. 16, Gesell-*

schaft für Wärmewirtschaft, Vienna, and research on the insulating properties of walls of buildings is also described in *Annales de l'Institut Technique du Bâtiment et des Travaux Publics,* **1,** *52.* An investigation of the use of gaseous fuel in warm-air furnaces for the heating of buildings is described in *Engineering Bull.* **18** (*6*), *Purdue University.*

CORRESPONDENCE

ON

PAPERS PUBLISHED IN FEBRUARY, MARCH, AND APRIL 1936 JOURNALS.

VOLUME 2, 1935–36.

Paper No. 5020.[1]

"Royal Docks Approaches Improvement, London."

By DUNCAN KENNEDY, M. Inst. C.E., and HUBERT EDWARD ALDINGTON, Assoc. M. Inst. C.E.

Correspondence.

Mr. A. C. DEAN suggested that the value of the Paper to those not Mr. Dean. [d]irectly interested in the development of the Port of London, and [t]o whom the details of construction were of major importance, was [so]mewhat impaired by what appeared to be a considerable measure [of] condensation. The points of discussion which followed were [th]erefore to be regarded not necessarily as forming criticism but as a [de]sire for more extended information, with particular respect to the [pi]ling operations.

The Authors had not explained the basis on which the set for [pr]e-cast piles had been specified (p. 24), and he presumed that the [or]iginal figure had been determined from the results of driving test [pi]les rather than by a general specification issued prior to com[m]encing work. The correlation of the specifications for sets given [by] the Authors with the stated maximum loads appeared to be [de]sirable for a proper comprehension of the principles involved. As [it] appeared from the Paper that the modified set (using a 3-ton [ra]mmer) gave by formula a better load-carrying capacity than did [th]e original set specified, it would be of interest to know why that [m]odification was used in conjunction with a reduced working-load for [lo]nger piles. It did not appear that the slenderness-ratio of the [pi]les could affect the matter in view of their extra lengths being for [th]e most part in stiff clay. He was unable to follow the Authors' [de]ductions on p. 24 in determining the factor of safety of the piles [in] relation to the relative proportions of live and dead loads coming [up]on them. He hoped that the number of trial bore-holes had not [be]en limited to the four shown in Figs. 2, Plate 1, but it would seem

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[1] p. 4 (February).

Mr. Dean. from the small cost of bore-holes given in the Appendix that th number was not very great; it might be thought that more pre exploration would have enabled a more consistent specification t be adhered to.

In the circumstances it was perhaps not surprising that th contractors had asked to be allowed to use an in-situ type of pil since many in-situ systems at present in operation permitted nc only of an easily-adjusted length but a better knowledge of th sub-soil through which the pile was driven, especially where deta particulars and values of sub-soil strata from bore-holes were a litt meagre. He did not appreciate the necessity of condition (c) o p. 25, as there was in his opinion no doubt as to the regular formatio of sound "Vibro" or other in-situ piles in the ground strata describe in the Paper. The application of withdrawal-loadings to the ca culation of frictional resistance was not likely to give results of an particular value other than academic interest. It would be matter of normal expectation that a "Vibro"-type pile with i corrugated surface would give a somewhat higher value than woul the relatively smooth-surfaced pre-cast pile. If that were not th case then the claims of various piling systems having as a speci qualification the existence of corrugations or other surface pr tuberances would be wholly discounted. The 17-inch "Vibro pile which was actually withdrawn was not a full-length pil but it gave a resistance to withdrawal of 54 tons on a length penetration of about 20 feet, or a frictional resistance of 12 cwt per square foot, a relatively high figure for some strata but n necessarily remarkable for the softer soils forming the upper strata the bore-holes. Proper estimation of the value of the test wou require the addition of particulars as to the interval elapsing betwe driving and withdrawal, which would very materially affect t result, especially in clay soils. The time-factor was of the greate possible importance in all matters relating to test-loadings and wit drawals of piles, and it might again be stressed that without su information test-results were practically valueless. The withdrawa test could not in any case be related directly to the work as execute He presumed, however, that it was in face of the low value of failu in *Figs. 16* and *17* that the working load per pile on the viadu work did not exceed a figure of from 35 to 45 tons, with an appare factor of safety of less than 2. Here, again, for a proper comparis the relative dates of driving were essential as information, as al were the respective curves of driving resistance. He asked t Authors to give that information in their reply.

The proportions of materials given in Table II (p. 28) for reinforce concrete piles were 3 to $1\frac{1}{2}$ to 1, but he presumed that a somewh

weaker mix would be used for the in-situ piles which were not subjected to driving stresses, since the consideration of density as a protection against damage to the reinforcement of the piles seemed unlikely in the circumstances. The surface treatment of concrete work was of interest, especially in view of the fact that the prevention of crazing and discoloration of finely-finished concrete could hardly yet be described as a universal achievement. He would be pleased to learn whether any special steps had been taken in the pre-cast work to obviate crazing, and whether any signs of that defect had yet become apparent. Mr. Dean.

He was not convinced as to the desirability of the type of construction used for the Barking road approach. The pervious and compressible ground shown in borehole No. 2 (Figs. 2, Plate 1) made it doubtful whether the upper soil would actually continue to carry the share of loading intended, and it appeared to him to be purely a matter of conjecture as to what the distribution of maximum loading would be. The addition of some 9 or 10 feet depth of concrete filling in association with a degree of uncertainty as to its incidence of load gave some reason to suppose that the addition of more piles, carrying a fully-supported flat deck, might very conceivably have given a more dependably-loaded structure at very little, if any, addition to the cost. He was unable to see that the fact mentioned by the Authors that no movement had been recorded was a criterion that the ground and piles were sharing the load ; unless a pile reached the point of actual failure (and even then it would be necessary to dismiss the certainty of help from neighbouring piles) there appeared to be no proof of the actual conditions. The thickness of the concrete filling would prevent any material deflection between piles, and it would appear that any live loading would automatically be transmitted to the piles, with the result that their settlement could only be obtained with a reduction of their factor of safety to an inordinately low figure. The tie-beams between the pile-caps, shown in Figs. 15, Plate 3, might apparently tend to induce unexpected stresses in the arch should they be deflected by settlement under the heavy live loading referred to in the Paper.

Mr. Frederick Grisley, who had been Assistant Engineer for the Barking Road section (including the railway bridge at Canning Town), observed that two light riveting hammers were used against the outsides of the shutters for about the first 6 feet lift of concrete in the abutments of the bridge above the hinge. It had been found that, owing to the mass of shuttering and the additional mass of concrete as it was deposited, the effect of the light hammer in vibrating the concrete was so small as to be almost negligible. The timber shutter under the hammer had been smashed to a pulp, and Mr. Grisley.

Mr. Grisley.

the hammers had been transferred to the vertical 6-inch by 2-in timbers supporting the boards. An ordinary 7-lb. sledge-hammer h been found to be more effective in shaking the concrete. Finally, t riveting hammers had been applied through dollies to the main rei forcement itself ($1\frac{1}{2}$-inch bars at 4-inch centres), care having be taken not to displace the steel; that method had proved to quite satisfactory. The hammers had not been in any way strapp to the shutters, but had been held in the hand.

It would seem that any vibrator, to be effective, should be pr portioned in its weight and in the frequency of the blows to t mass of shuttering and concrete in the work. If the steel skelet were sufficiently rigid to be vibrated without displacement, t bars themselves would act as tampers and the concrete would consolidated around the steel in an ideal manner. The process cou obviously only be carried on during the initial setting time of t concrete that had been first deposited, although, according to tes by Mr. R. V. Allin (p. 38), that time could extend to some 5 hou without harm.

The use of a pneumatic hammer was merely a contractor's e pedient. He would suggest that suitable portable apparatus f vibration would consist of a variable-speed electric or air mot driving an unbalanced flywheel, with suitable means of adjusting t unbalanced weight and its radius of gyration, the whole arrangeme embodying quick-grip attachments to shuttering or steel. By th means the periodicity and magnitude of the vibrating force cou be varied to suit the size and mass of the work, and the simp harmonic motion would be less destructive or disturbing than t blows of percussion tools.[1]

Mr. Hill.

Mr. J. R. Hill observed, with reference to the effect of delay the placing of concrete after mixing, that concrete-core tests h been made in 1933 on the Guildford-Godalming By-Pass by the Ro Research Laboratory of the Department of Scientific and Industr Research. During the progress of the work cores had been tak from the concrete carriageway from time to time in order to ascerta *inter alia*, their crushing strength; towards the latter end of t work a central concrete-mixing plant had been erected adjacent the Hog's Back, to which concrete had been transported in special constructed lorries to the remaining sections of the by-pass wh the carriageway had not been constructed. The concrete had be transported from the central mixing plant to Milford, a distance 4 miles; the journey had taken approximately 80 minutes, a

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[1] Since the above contribution was submitted, commercial vibrators similar type to that suggested have been marketed.—F. G.

cores taken from the carriageway at Milford had showed crushing strengths ranging from 2,900 lbs. per square inch to 4,590 lbs. per square inch, compared with crushing strengths of 1,670 lbs. per square inch to 1,960 lbs. per square inch for concrete which had been laid immediately after mixing. That was contrary to the usually accepted view that it was essential that concrete should be laid in its final position prior to the initial set taking place; it was not, however, thought that much advantage could normally be taken of that development, for both practical and financial reasons. Mr. Hill.

Mr. H. W. S. HUSBANDS considered that the layout of the new Barking road bridge and approaches called for no adverse criticism, as the approaches to the old bridge were hopeless. With the Silvertown Way, however, the case was different, and it seemed surprising that such expense should have been incurred simply to provide a wider and duplicated dock-approach road and to get rid of the railway level crossings, without apparently any attempt having been made to eliminate any of the road cross-traffic. The right-angled junction of the old Victoria Dock road was mentioned on p. 6 as an obstructive feature, and in the new scheme the improvement was confined to cutting off the corners and providing a small island, which was not even a roundabout, to give adequate approach curves to the wider road. All traffic from London to the docks had here to turn right, thus holding up all the Barking road traffic, whereas it would have cost little more to have carried the Silvertown Way under the Barking road, or vice versa, so that that traffic and that from the north, via Manor road, to the docks would not have interfered with the Barking road traffic at all. In view of the proximity of the railway on the western side that might have entailed moving the junction perhaps 50 yards farther east to leave room for connecting by-pass roads to complete the junction. No insuperable difficulty seemed to exist, although the plans in the Paper gave insufficient detail in that respect for definite location. Mr. Husbands.

He did not generally favour the type of viaduct or elevated road (like the Silvertown Way) running between parallel roads at a lower level, and he considered it better to have a wider road at the higher level where the more valuable frontages could be utilized. The space under such viaducts was of little use and frontages to the lower roads were of little value. No doubt in the case under consideration the bad foundation and the short distance between the two main bridges was some justification for the method adopted. It was also noticeable that the spur roads were all on one side, so that some cross-traffic was engendered on the viaduct itself; that was a bad feature which could have been avoided at small additional cost.

He had read the Paper with great interest, and he wished to

Mr. Husbands. congratulate the Authors and all concerned on the excellent results c their efforts. The precautions taken to avoid undue settlement o such doubtful foundations were of especial interest, and erred, anything, on the side of over-caution ; the efficiency of the executio and the great value of the scheme as a whole were beyond questio although the value might have been enhanced, as had already bee suggested.

Mr. Porter. Mr. J. P. Porter mentioned that, with regard to the informatio given on pp. 24 to 26 regarding piling, it was stated that for a 3-to hammer falling 3 feet, the specification of an equivalent set c 0·1 inch was stiffened to 0·06 inch, presumably with the intention c increasing the supporting value of the piles. It could be deducec however, from the Hiley formula [1] that decreases in the set belo 0·1 inch involved only negligible increases in the safe supportin value of a pile, and that where an appreciable increase was require additional penetration should be effected by increasing either th hammer weight or the fall, or alternatively the size of the pile shoul be increased.

It would be of considerable value to those interested in the sup porting value of piles if the Authors would give as full records a possible of the driving and loading of all the test piles referred t particularly those piles which were loaded with kentledge, wit details of the nearest bore-holes in each case. The effective cros section of the pre-cast piles was about 1·3 square foot whereas th effective cross section of "Vibro" piles was about 1·6 square foo and it was therefore to be expected that the bearing capacity of th "Vibro" piles would be at least 25 per cent. greater than that of th pre-cast piles driven in similar ground. The records given showe that the increase was of that order.

The loading tests given in *Figs. 16* and *17* were not complete comparable as between the two types of pile, in that the times durin which load was applied varied considerably for the two types. H suggested that test-loading should proceed by increments of 10 to at fixed intervals of at least 24 hours, and that as soon as "rap settlement" was reached at least 5 tons of the load should b removed at once, whilst if settlement continued further kentled should be removed in 5-ton amounts at short intervals until "rap settlement" ceased. That method was suggested as it had frequent been noted that greater force was required to start re-driving pile some time after it had been driven, or to start withdrawa than was necessary to continue such re-driving or withdrawa The lesser and not the higher force was the obvious limit of safet

[1] A. Hiley, "Pile-Driving Calculations with Notes on Driving Forces, a Ground Resistance," Journal Inst. Struct. E., vol. viii (1930), pp. 247 and 278.

Mr. R. W. WALKER observed that, in view of the very substantial advantages which were known to be obtainable by the use of aggregates of maximum density, it would be of interest to know whether consideration had been given as to what extent the quality of the concrete might have been improved, and what saving might have been effected had means been adopted for the control of the sieve analysis of the aggregates. He would draw attention to the fact that, in addition to the attainment of increased density (to effect which vibration of the concrete had been adopted), and increased strength (clearly a consideration of considerable moment in relation to the reduction of dead load, and in view of the limited construction depth sometimes available), the "yield" of finished concrete might, by the use of aggregates of maximum density, have been considerably increased. Mr. Walker.

Plant was now available whereby the sieve analysis of aggregates could, in practice, be economically controlled. Reference had been made on p. 31 to trouble having been experienced with the aggregates, and to the aggregates having varied within a wide range even after changes had been made. The solution would appear to be the adoption of aggregates of controlled sieve analysis. The reduction in strength of the concrete by increase in the water-content was mentioned; in that connection, difficulty was commonly experienced in applying the water/cement ratio unless the sieve analysis of the aggregates remained constant. Further, "blending" of aggregates had a beneficial effect as regards workability.

As far as the proportioning of the ingredients of the concrete was concerned, and in view of the considerable sum which must have been spent on the inspection of such proportioning, it was of interest to note that plant of such infallible reliability was now available as to eliminate any necessity for inspection. The manual control of measurement was dispensed with, and as shortage of any ingredient would automatically stop the plant before any defective product could be issued, the plant was incapable of producing a product other than that in accordance with the settings, which could be locked.

The AUTHORS, in reply, observed that the provisional set originally specified for pile-driving ($\frac{1}{2}$ inch for ten blows with a 2-ton hammer falling 3 feet 3 inches) had been based on earlier experience of piling operations carried out in the same district. When a longer pile than anticipated had been found to be necessary, a 3-ton hammer had been prescribed on account of the extra weight of the pile, and the set and fall had been modified as stated on p. 24. That change had not been intended to increase the load-carrying capacity of the piles, as suggested by Mr. Dean. Whether it had done so or not The Authors.

The Authors. would depend on the size of the particular pile, as the heavier the pile the less its carrying capacity for a given set, weight of hammer and drop. The reduction of the maximum working load from 60 to 50 tons per pile naturally allowed a greater margin of safety, and that had later been somewhat increased by altering the set to two hundred blows per foot as stated.

The Dutch formula [1] had been employed in the early stages of the work for adjusting the set to the varying loading of the piles but the results had not been found to be reliable when checked by the loading tests, and its use had been abandoned. Mr. Hiley's formula,[2] to which Mr. Porter had referred, was generally agreed to be the best now available, and if the coefficients were carefully chosen with due regard to the observed behaviour of the piles when driving, a reasonably close approximation of the bearing value could be obtained. The Authors were of the opinion, however, that it was a mistake to rely entirely on any formula, and that, wherever practicable, test piles should be loaded, preferably to failure, as a check on whatever formula might be employed.

With regard to the relative effect of the live and dead loads on the factor of safety, a pile would support for a short time a load which, applied for an extended period, would cause it to settle. It might be contended that a continuous stream of traffic, if maintained for several hours, would operate in that respect in the same manner as the dead load, but in the present case the critical factor in the live load was not ordinary traffic but the hypothetical 100-ton lorry on four wheels for which provision had been made. The total number of trial boreholes put down to ascertain the nature of the ground was eleven, and the Authors had no reason to believe that any addition to the number would have been of material advantage.

Mr. Dean had questioned the necessity for extracting one of the cast-in-situ piles for examination. The Authors considered that to have been a very desirable test, and the result had given satisfaction to all concerned as demonstrating the soundness of the piles as driven. Many engineers whose experience with cast-in-situ piles had, in certain circumstances, not been so happy, would appreciate the value of that proof. The information obtained as to frictional resistance had not actually been used for any purpose, but it remained as an interesting record. The time elapsing between the driving and extraction of the "Vibro" pile was 23 days. The test shown in *Fig. 16* (p. 25) had been applied to the piles 8 weeks after they had

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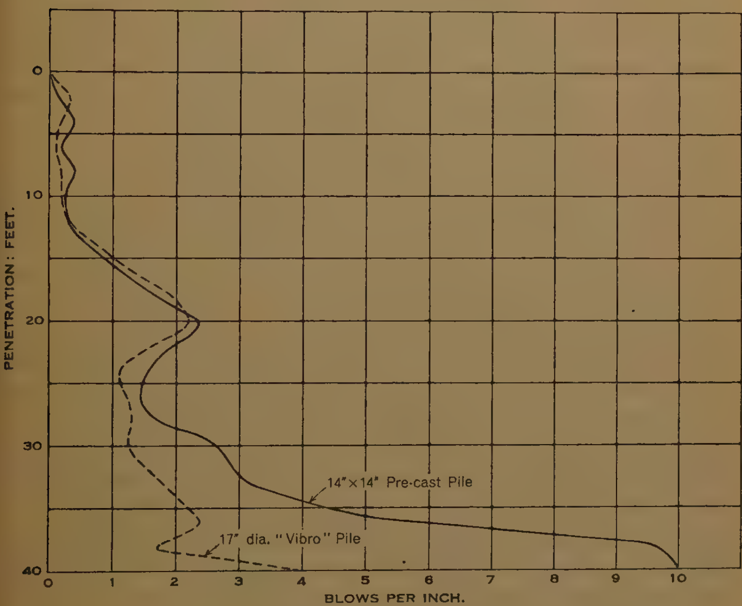
[1] A. C. Dean, "Piles and Pile Driving," p. 140. London, 1935.

[2] Footnote 1, p. 614†.

been driven, and that shown in *Fig. 17* had been commenced 18 weeks after driving. The driving resistance in the former case was shown in *Fig. 21*. The Authors.

Mr. Porter had referred to the comparative cross-sectional areas of the "Vibro" and pre-cast piles as an indication of the ratio of the bearing capacity that might be expected. The Authors suggested that a fairer comparison would be their surface-areas, which, in the case of a 14-inch square pile and a 17-inch diameter round pile, were practically the same. The extra bearing capacity of the

Fig. 21.



"Vibro" pile was more likely to be due to its irregular surface having greater frictional resistance than that of the pre-cast pile. No change in the proportions of the concrete had been made when "Vibro" piles were substituted for pre-cast piles.

In referring to the pile-supported concrete fill in the Barking road approach, Mr. Dean had suggested that a fully-supported flat deck might have been substituted at little, if any, additional cost. That could have been done, but in the circumstances such a structure would have been more troublesome to construct, apart from the question of cost. The new road ran at an oblique angle into the old road, which was under heavy traffic. The area of new road in question was not

The Authors. available for carrying out the work in one operation, and the method adopted lent itself to piecemeal construction. With regard to the pre-cast concrete blockwork, no special steps had been taken to obviate crazing, and little trouble on that account was experienced.

Mr. Grisley had referred to an occasion when, in vibrating the concrete of the railway bridge at Canning Town, the timber shutter under the hammer had been reduced to pulp. That had probably been due to the use of too heavy a hammer, or to its application for too long a period. Actually, with a mass of concrete such as in the above bridge, vibration applied to the forms (whether to the sheeting or its supports) would only be effective in consolidating the outer layers of concrete, and further vibration of the reinforcement or internal concrete would be necessary. In the other parts of the work where vibration had been called for, the sections were of smaller dimensions, and vibrating the forms had generally been sufficient. The light riveting hammers or other percussion tools employed had been the most suitable type of appliance available at the time, but since then various special types of high-frequency vibrators had come into use in Great Britain. In referring to Mr. Allin's interesting experiment to determine the effect on the strength of concrete of allowing it partially to set before ramming it into moulds, Mr. Grisley appeared to have stretched Mr. Allin's conclusions beyond the point that the latter intended. Mr. Allin had been careful to emphasize that his experiment on the concrete permitted an intensity of ramming rarely practicable under working conditions. The Authors, in the light of present knowledge, would not recommend anyone to vibrate concrete 5 hours after it had been deposited. The figures given by Mr. Hill for comparative strengths of concrete placed immediately after mixing and placed after having been transported 4 miles, were very interesting. The Authors could not help feeling, however, that an average increase of strength of over 100 per cent could hardly be entirely due to a delay of 80 minutes in depositing the concrete.

With regard to the grading of concrete aggregates mentioned by Mr. Walker, no detailed sieve analysis had been specified, the grading of the materials having been judged by their appearance and checked by occasional sieve analysis for any apparent deficiencies. No great additional cost had been incurred, as suggested by Mr. Walker, in the inspection of proportioning, the work having been carried out by the Resident Engineer's staff as part of their normal duties. The use of aggregates of maximum density was certainly desirable. Unfortunately, there was no general agreement among authorities as to the ideal grading to give maximum density and workability, and it was found that aggregates from different sources did not give

The Authors.

the best results with the same grading. It would be a great advantage if some general standard were adopted for each type of aggregate, and if materials graded to such standards could be obtained in the market at reasonable cost. The Authors were not familiar with the plant referred to by Mr. Walker for the automatic control of sieve analysis, and to which he ascribed such a high standard of reliability.

Mr. Husbands had suggested that the junction of Silvertown Way with the Barking road should have been constructed as a fly-over junction. The Authors agreed that, if a site was suitable and if the work could be carried out at a reasonable cost, that form of construction was of great advantage at the junction of roads carrying heavy and continuous traffic, particularly in dealing with an ordinary four-way crossing. In the case in question, however, the junction was a "T" junction and was in a thickly-populated built-up shopping area. The construction of a fly-over would have necessitated the demolition of a large amount of additional property, with consequent re-housing. Further, owing to the position of the railway station, together with the railway bridge and the gradients, the engineering costs would have been heavy. The Authors could not agree that it would have cost little more to have carried the Silvertown Way under the Barking road or vice versa. There could be no comparison between the right-angled junction of the old Victoria road with Barking road and the new junction of Silvertown Way with Barking road. The old junction had been adjacent to the railway bridge, on a steep gradient, and with a carriageway only 21 feet in width. The new junction had been carried some 80 yards eastwards from the railway bridge, and Silvertown Way joined the Barking road practically on the level; it was 80 feet in width with easy curves. The movement of traffic was controlled by vehicle-actuated light signals, which had proved in practice to be thoroughly satisfactory in handling the heavy volume of traffic in both Silvertown Way and Barking road. The easy controlled movement of traffic at the junction demonstrated that there would have been no justification in the case in question for the construction of a fly-over.

The lower parallel roads had been designed to avoid the possibility of frontages developing on the viaduct, with the consequent standing of vehicles alongside the curb: the viaduct was now entirely free of standing vehicles. The purpose of the scheme was to give rapid access to the docks. That had been achieved, but it would have been largely defeated if frontage development had been encouraged along the viaduct. The cross traffic on the viaduct itself to the spur roads operated with ease owing to the freedom of movement of traffic. The Authors did not consider that the additional costs which would

The Authors. have been necessary with any other arrangement would have been justified.

Mr. Aldington. Mr. ALDINGTON, in replying further to the Discussion, observed that the scheme for the construction of the Victoria Dock had been promoted by Mr. G. P. Bidder, Past-President Inst. C.E., the contractors having been Messrs. Peto, Brassey and Betts. Those parties had already interested themselves in the development of the marshland between Bow Creek and Gallions to the extent of promoting and building a branch line of the Eastern Counties Railway from Stratford to North Woolwich. The Victoria Dock had been constructed by the Victoria (London) Dock Company under powers conferred by Act of Parliament (The Victoria (London) Dock Act, 1850, 13 & 14 Victoria, Cap. 51), and had been opened in 1855. The land had been purchased by the Dock Company, and records showed that it had been obtained from private owners, there having been no mention of the North Woolwich Land Company in the documents. In 1864 the London Dock Company and the St. Katharine Dock Company had amalgamated, and had purchased the entire Victoria Dock from its original owners with the exception of the pontoon dock, which had remained private property. The pontoon dock had been sold by the Victoria Dock Company to the Thames Graving Dock Company, Ltd., in 1860. From 1866 until 1897 it had been the property of the Victoria Graving Dock Company, Ltd., and in 1897 it had been purchased by the London and St. Katharine Dock Company. The London and St. Katharine Dock Company, which owned the Victoria Dock, had opened the Royal Albert Dock in 1880. The King George V Dock had been constructed by the Port of London Authority, and had been opened by His late Majesty King George V in 1921.

Paper No. 5035.[1]

"The Flow of Water through Rectangular Pipe-Bends."

By POWYS DAVIES, M. Inst. C.E., and SHIVRAM VASUDEO PURANIK, B.E.

Correspondence.

Mr. Addison. Mr. HERBERT ADDISON observed that during the past year he had been making a series of experiments on pipe-bends, with almost the same object as the Authors' experiments. His own tests had been made

[1] p. 83 (February).

on bends of square section, both of carefully-machined brass and of unmachined cast iron, so that when the results were available it would be most instructive to compare them with the results obtained from the teak-wood bends used by the Authors. He hoped to be able to present his results to The Institution in the near future. Mr. Addison.

Mr. D. G. ELLIOT was of opinion that, while not definitely so stated in the Paper, it would appear that the Authors were assuming that a Pitot tube recorded velocity heads, $V^2/2g$. Although in the case of pipes a Pitot tube appeared to record velocity heads, he wished to point out that in general the impact head, V^2/g, was recorded by the tube. The apparent divergence from that rule which took place when a Pitot tube was used in a pipe might be explained by the reasoning given in T. Merriman's and T. H. Wiggin's American Civil Engineer's Handbook [1] and in a paper [2] by Messrs. G. S. Williams, C. W. Hubbell, and G. H. Fenkell. Mr. Elliot.

The Authors stated on p. 103 that "It would appear at first sight to be impossible for the Pitot tube to record a momentum of flow greater than that which occurred in a direction normal to its orifice, but the fact remained that it did record such a momentum." He felt, however, that the reasoning cited above offered a simple explanation of such a phenomenon; namely, that the velocity at the wall had approached a magnitude comparable with that at the centre. He was of the opinion that the Authors' experiments on the open horizontal flume had proved only that the velocity at the walls of the flume was not negligible. As turbulence of flow was not the only factor affecting wall velocities (although admittedly it was a very important one), he could not accept as justifiable the "reasonable inference" reached by the Authors from the results of their experiments.

In conclusion, he would like to express his appreciation of the data which the Authors had made available.

The AUTHORS, in reply, observed that Mr. Addison's experiments ought to provide data of considerable value, and they awaited their publication with interest. They were unable to accept Mr. Elliot's suggested explanation of the Pitot-tube results. The authorities whom Mr. Elliot quoted had pointed out that it made very little difference which form of expression was adopted (namely $V^2/2g$ or V^2/g) because the change was provided for in the coefficient of the instrument, a conclusion with which the Authors agreed. Furthermore, the nature and magnitude of the flow at the walls of the flume were constant throughout the experiment, and therefore could The Authors.

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[1] p. 1369. 5th Edition. New York, 1930.

[2] "Experiments at Detroit, Mich., on the Effect of Curvature upon the Flow of Water in Pipes." Trans. Am. Soc. C.E., vol. xlvii (1902), p. 1.

The Authors. not affect the results. It seemed likely, however, that the size of the orifice had a good deal to do with the results, and that if it had been practicable to have had an orifice of, say, 1/100 inch diameter, the results might not have been abnormal.

Students' Paper, No. 918.[1]

"Modern Permanent-Way Design."

By Ronald Bridgman, Stud. Inst. C.E.

Correspondence.

Mr. Peters. Mr. Reginald Peters observed that the Author seemed to have been a little hasty in assuming that the subject had not been properly treated before. More than 25 years ago he had been engaged on works embracing extensive permanent-way layouts, and at that time the "old Caledonian" method of calculation had been found inadequate and had been modified on the same principle as that suggested in the Paper; further, he had not been alone in the field. Both as a maker and a user of crossings his attention was first drawn to the degree of refinement to which the calculations set out in the Paper had been carried, to match which the rails would require to be very accurately machined, say at the crossing-splice to within $\frac{5}{1,000,000}$ inch. It was, he considered, pertinent to ask what value such particularity possessed in relation to material which could not and need not be accurate to within many hundred times the limits which the Paper sought to impose. Taking, as an example, the outer curved track of the double junction on p. 149 and starting from the toe of the switches, oppositely corresponding portions of the axes of the two rails might be set down as follows:—

Outer rail.	*Inner rail.*
flat	flat
arc	arc
flat	arc
arc	flat
flat	flat (one slightly leading
arc	arc
flat	arc

It was obvious that the two axes could not be parallel and, in

[1] p. 135 (February).

practice, approximate parallelism was obtained by using non-circular arcs. The marginal variations involved were minutes of angle and feet of radius or lead, whilst the Author's Tables implied that they were half seconds and thousandths of an inch. If practical accuracy was the aim, the Paper could have been very considerably condensed. Standard layouts comprised 33 per cent. of point-and-crossing work, and the dimensions had been sufficiently accurately calculated and employed for years; 66 per cent. consisted of applying standard material to non-standard conditions. For that purpose drawings to a proper working scale were the quickest and most reliable guides. The Author's pronouncement against them in his "Conclusion" might be attributable to his advocacy of the peculiarly unworkmanlike and diminutive scale of $16\frac{1}{2}$ feet to an inch. For the remaining 1 per cent., using such proportions figuratively, a few general equations and a Table of constants furnished all the theory required. In his opinion it was necessary for theory to take more note of limiting conditions. Mr. Peters.

The AUTHOR, in reply, observed that Mr. Peters criticized the calculations for being carried to an impractical degree of refinement. If the final dimensions had been given to the same degree of accuracy as that used in the working-out, that would have been the case. In Appendix II, Tables III, V and VI, however, it would be seen that radii were given finally in decimals of a chain, running dimensions to $\frac{1}{8}$ inch, and angles of crossing to minutes (that was to say, the difference between angle of 1 in 9 feet 6 inches and 1 in 9 feet 7 inches was 4 minutes). That degree of accuracy was considered practical in the final dimensions, but, to obtain it, it was necessary to use a greater degree of accuracy in the working-out, owing to the very acute angle of the triangles that had to be solved. For example, in calculation No. 6 (Appendix III), The Author.

$$\tfrac{1}{2}\,A\hat{O}C = 0^\circ\ 10'\ 2{\cdot}3''$$
$$\text{and } AC = 6{,}600 \sin \tfrac{1}{2}\,A\hat{O}C = 19 \text{ feet } 3 \text{ inches.}$$

An error of 1 minute in $\frac{1}{2}$ $A\hat{O}C$, suggested as being practical by Mr. Peters, would lead to an error of 1·92 foot in AC, and crossing C (angle 1 in 10 feet 4 inches) would be thrown approximately $2\frac{1}{4}$ inches out of alignment. Whether or not that was unnecessary refinement depended on the standard of smooth running required from the track.

The time involved in the calculations was small (the longest example given, No. 6 (Appendix III), took on an average 2 hours for each double junction on a curve), whilst the graphical errors, inevitable in dealing with curved tracks even when a large scale was used, were eliminated. It was thought, therefore, that the

The Author. system of calculation described did justify itself, while the layouts designed by that method had shown very satisfactory alignment in practice.

Paper No. 5047.[1]

"The River Foyle Crossing (Londonderry Waterworks)."

By Walter Criswell, O.B.E., M. Inst. C.E.

Correspondence.

Mr. Cotterell. Mr. A. P. I. Cotterell was especially interested in the remarks on p. 195 about the nature and the bearing-power of the river-bed. They tended to show that although the surface materials formed a slurry when saturated with water, yet at a depth below the zone of saturation they would bear an appreciable load, amounting to as much as 1 ton per square foot at a depth of 4 feet. The Author had not stated the composition of the slurry-like material, and whether clayey or sandy ingredients were the chief characteristic. Apparently, however, below the scour-line and when protected from the influence of irregular scour due to spates in the river, that load could be carried indefinitely.

Some years ago he had had occasion to investigate the soft subsoil of the alluvial flats bordering the mouth of the river Usk, near Newport, Mon. It had been proposed to construct settlement-tanks with a maximum load when full of water of about 1 ton per square foot; heavy buildings in the neighbourhood had, however, settled considerably, and it had been desired to make certain that a settlement-tank, if constructed at the spot in concrete (reinforced where necessary), would stand up to the work without breaking its back. The subsoil was somewhat firmer than the soft underwater silt described by the Author, and consisted of a soft alluvial soil of a blackish blue, but containing also much sand. In order to test the bearing-power at a depth of 6 feet, an excavation about 9 feet 6 inches by 8 feet 3 inches in area had been made, and a box 16 square feet in area and 6 feet deep had been loaded to a total weight, including the box, of 21·45 tons. The inter-space between the box and the timbering had also been loaded with dry bricks as a counterbalance to the specially-loaded area, a space between the bricks and the box of not less than 3 inches having been maintained.

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[1] p. 190 (March).

The total settlement had been 0·23 inch, of which 0·08 inch had taken place early when bricks had been substituted for a sand surrounding that had previously been there. The period of the test had been 23 days, and the total load had been 1·34 ton per square foot. The test proved that soil considered to be unstable for ordinary building was capable of bearing a considerable load without difficulty if it were properly spread. Mr. Cotterell.

It was a little difficult to follow the statement on p. 196 that one of the 12-inch pipe-lines for the river-section would, if used by itself, carry 3,000,000 gallons, or three-quarters of the full supply. If the hydraulic gradient of the Foyle siphon was 1 in 200 (p. 192) on either side of the actual river-crossing, and the two 12-inch pipes were laid with a similar hydraulic gradient, then one only would take less than 2,000,000 gallons per day, and not 3,000,000 gallons (or three-quarters of the full supply).

Mr. W. I. Thatcher drew attention to a statement on p. 211 made by Mr. W. J. E. Binnie that ordinary armoured hose-pipes had been used at Fleetwood, ". . . one 12 inches in diameter and several smaller ones." If that referred to a pipe-line put across the river Wyre by the United Alkali Company, Limited, and now owned by Imperial Chemical Industries, Limited, which was the only under-water pipe-line at Fleetwood, a 12-inch diameter armoured hosepipe had never been used for that purpose. All the pipes of that nature had been and still were, 4 inches in diameter with cast-iron couplings and loose steel flanges. There were eleven such pipes, each made up from about 20- or 30-foot lengths of armoured hosepipe, and it was quite true that some of them had been in use for over 30 years. He had been responsible for the maintenance, repairs and relaying of those pipelines during the last 8 years, and he was fully acquainted with their past history. The mistake about the diameter had probably arisen owing to the fact that the ends of some of the 4-inch services were coupled to a 12-inch diameter cast-iron main laid on rubble and concrete groynes in the bed of the river Wyre and ending at the edge of the low-water channel, across which the armoured hose-pipes were laid. Mr. Thatcher.

Mr. R. C. S. Walters thought that some details of two short crossings of the Thames and Ray, which had been recently constructed for the Swindon Corporation Waterworks, might be of interest. Those crossings were respectively about 70 and 100 feet in width, and had had to conform to the regulations of the Thames Conservancy. As at Londonderry, the pipe-line was 18 inches in diameter, and it was connected at a few yards from each bank to two 12-inch pipes under the river; the two pipes were controlled by sluice valves. The pipes were of cast iron (B.S.S. Class C) wholly Mr. Walters.

Mr. Walters. encased in concrete, both on the end-ramps and under the river-bec the top of the pipe being about 8 feet below the water-level an 2 or 3 feet below the river-bottom. The work had been carried ou in the dry by sheet-piling in two operations, each extending half-wa across the river, and as the banks had been interfered with by th excavation of the pipe-trench they had been replaced by piles 15 fee long, secured by tie-rods and waling. The pipes were provided i duplicate to minimize the risk of a burst pumping-main, particularl as water in the pumping-main was liable to surge when the centri fugal pumps were stopped. The pipes were provided with hatche on each bank which could be opened for purposes of scraping th main if that should ever be required.

The Author. The AUTHOR, in reply, observed that the silt on the south-east sid of the river Foyle consisted of extremely fine sand with a proportio of alluvial soil; in general, it closely resembled the silt near Newport Allowing for the greater depth at which the Newport test had bee made, there was a notable similarity in the results. It wa necessary to appreciate the differences in the methods of testing. I the test at the river Foyle a circular plate, or piston, 13½ inches i diameter had been loaded with a pre-arranged load and had bee allowed to sink into the soil until it had come to rest. In the tes described by Mr. Cotterell a weighted box had apparently bee lowered into a timbered hole previously excavated to the final depth Although with the latter method of testing the disturbance of th soil during the process of excavation might affect the amount of th recorded sinkage, the method had the advantage of reproducin fairly closely the actual working conditions which might be expecte to arise during the building of a concrete tank.

The twin lengths of 12-inch pipe, each about 1,300 feet long, ha been inserted in the Foyle siphon at its lowest point, where it crosse under the bed of the river. It might be of interest to examin more fully the reasons for using the particular size of pipe. In th case of a high-pressure steel pipe, fitted with expensive ball-and socket joints and laid in the manner described in the Paper, the cos of both material and labour increased rapidly with any increase i the diameter, whereas the extra cost of a slightly larger pipe used i ordinary trench-work was proportionately much less. The principl adopted for the Foyle siphon had been to reduce the diameter, an consequently the cost, of the most expensive section, equating tha saving with the extra cost of increasing the diameter of tha part of the siphon which could be laid cheaply. In practice th diameters had been designed to give a total flow of 4 million gallon per day with both of the subaqueous pipes in use, and 3 millio gallons with one out of action. The "dry-weather" yield of th

catchment-area was $3\frac{1}{2}$ million gallons, and of that amount $\frac{1}{2}$ million gallons could, if necessary, be distributed from a service-reservoir on the south-east bank, without crossing the river. The reduction in flow to 3 million gallons with only one subaqueous pipe in action was, therefore, considered to be justified by the great saving in cost due to the use of the smaller pipe. A test-flow of 4 million gallons had been successfully passed through the twin pipes used together, and 3 million gallons through each of the pipes used singly. The Author.

Papers Nos. 5041 and 5043.[1]

"St. Germans Sluice and Pumping-Station."

By ROBERT GEORGE CLARK, O.B.E., M. Inst. C.E.

and

"The Effect of Flood-Relief Works on Flood-Levels below such Works."

By ERIC CHESTER HILLMAN, M.C., B.Sc., Assoc. M. Inst. C.E.

Correspondence.

Mr. E. B. BALL, Jun., drew attention to the economical use that ad been made of the space available at St. Germans; that result ad been chiefly brought about by the symmetrical arrangement of he whole installation. A typical example of the economical use of pace was to be seen in the way the cooling tanks had been incorporated in the concrete structure between the two sections of the umping-station. Mr. Ball.

With regard to details of the sluice-gates, although no particulars ere mentioned in the Paper, he believed that the staunching rrangement between the vertical side staunching-tubes and the ntel-joint consisted of a rubber member. He would be interested know whether that had proved a satisfactory arrangement, and hether deterioration of the rubber had been noticed during the eriod of working of the station. If Mr. Clark could furnish any gures of the leakage of the gates under maximum head they would ove of considerable interest.

Mr. A. C. DEAN observed that the cost of the St. Germans installa- on was given as £224,000; that seemed a considerable sum, and Mr. Dean.

[1] pp. 377 and 393 (April).

Mr. Dean. he would be interested to learn how it was divided between plant and constructional works, respectively. The formation of the floor of the main structure was of a heavy character. It would appear from Mr. Clark's description, and from Fig. 5, Plate 1, that not only was there a total depth of some 12 feet of concrete resting on the piles but that there was, as part of that concrete, a reinforced raft at the upper level. It was difficult to see why a raft should be required in those circumstances, except in so far as the loads would be required to be distributed from the floor to the various piles. The existence of that 12-foot thickness of concrete would probably load the piles to somewhere between 15 and 20 tons each before taking into account the superimposed floor loads. Mr. Clark had not explained why the decision had been made, and it was difficult to see why confidence could not have been placed in an ordinary piled foundation supporting a reinforced-concrete floor slab, especially as the stability of the whole foundation had been augmented by driving raking-piles. Mr. Clark mentioned that the bearing capacity of the clay had been checked by driving a pile but Mr. Dean had some difficulty in appreciating that the driving of a pile could give a result which could be reconciled with any definite conclusion. A penetration of 34 feet into the Kimmeridge clay could better be appreciated if the set which had been considered to be reliable had been mentioned. The phenomenon mentioned on p. 38- regarding the lifting of piles by subsequent driving was not unusual especially in clay and with piles at the relatively close centres of 5 feet. Mr. Clark did not specify the "much more severe test" which had been applied to the piles which had lifted, nor was the Paper clear in the reference to "any further measurable movement." Reference had been made to the great care taken in obtaining a uniform size of reinforcing link, but in the ordinary method of manufacture of links it was difficult to see why there should be a tendency for any difference of size to occur, assuming that the links were first made and then fitted complete on the longitudinal reinforcing bars, in which case (as their sizes would be uniform) no question of unequal tautness could arise.

Assuming that the piles were made of ordinary Portland cement the time allowed to mature seemed very low. If, however, a rapid-hardening cement was used there was nothing exceptional in the successful driving of a pile in 5 days after casting. Mr. Clark had described on p. 389 the cutting off of the reinforcement of the pile within the raft, but it would appear, as before mentioned, that there was really no necessity for the reinforcement to have been taken to that high level, and the piles could have been driven on various in-situ systems from raft-level and the reinforcement provided on-

a few feet above the bottom of the mass-concrete ; or presumably, Mr. Dean.
pre-cast piles could have been driven from the level of the underside of the mass-concrete, assuming that the great thickness of the latter was necessary in any event.

Mr. Clark had referred to the line of steel sheet-piling driven across the outfall channel, and it would be useful to know how that was treated at its point of intersection with the side walls of the channel. The latter appeared to be heavy concrete walls with a concrete backing, according to the information given in Figs. 2, Plate 1, and their stability in the difficult conditions of ground which were described in the Paper seemed to be a matter of considerable interest.

Mr. C. E. Farran asked Mr. Clark if the need for the St. Germans Mr. Farran.
pumps would still remain were the estuary of the Ouse to be reconditioned. The increased efficiency of the internal Boards' fenland pumps had resulted in a need for increased storage in the main carrier drains ; given the improved low water of the spring tides, would it have been possible at reasonable cost to find sufficient storage by bank-raising or by moving raised banks farther apart, or in any other way ? He would also like to know if he were correct in assuming that the St. Germans pumps were run only in time of flood and for those periods of the day when the sluice was tide-locked, or would they, at times, be run for several days on end ? He would ask Mr. Clark to give some indication of the number of hours or days the pumps were likely to be in use during a year.

It would be of considerable interest to learn what the estimated or actual running cost per acre would be. The farmers had already, he supposed, a heavy drainage rate to pay for the upkeep of drains and for pumping the water into the main carriers ; would the new outfall annual charges add appreciably to the rate ? Given a reasonably low low-water level, the problem in schemes of the type under consideration was to decide whether it was more economical to provide adequate storage and sluices, or to provide pumping machinery. The balance was usually weighted in favour of the former alternative because of the saving in the occupier's rate needed to cover the annual cost of pumping. He did not wish to infer that in the case of St. Germans there was any alternative to pumping, but he considered that in cases where works on the main river could produce the required low-water level, the expenditure should be made on such works rather than on pumping plant with an ill-conditioned river.

It would have been of considerable interest, and would have enabled him to obtain a clearer grasp of what Mr. Hillman had in mind, if he had briefly described the Nottingham Flood Protection Scheme, from the consideration of which particular case he had been

Mr. Farran. led into generalizations. Mr. Farran understood that the flooding o an area of about 6,635 acres was to be prevented by providing a additional channel, referred to as a by-pass, to convey the wate which now caused the flooding from some point above the city t some other point below it. It appeared that the bank-full capacit of the river for the length where it was to be supplemented wa 9,000 cusecs, but that above the area considered it was capable o carrying the whole flood-flow of 22,820 cusecs. The problen Mr. Hillman was attempting to solve was, apparently, whether th river was able, below the point where the by-pass rejoined it, t convey within its banks the whole flood-flow of 22,820 cusecs, and i so, by how much the flood-stage would be raised and the peal advanced by reason of the former overflow having been prevented Mr. Hillman also gave the impression that the whole overflow tool place over one comparatively short length of bank, which he callec the "junction."

The first conclusion Mr. Hillman had arrived at (on p. 396) was that the effect of a by-pass on the flood-levels below the point of rejoinin the main river would be nil. The gist of the argument leading t that conclusion was that if a given quantity of water were conveyec through two channels the sum of whose hydraulic capacities wa equal to that of the one they replaced, the discharge would be th same in both cases, and the effect below the point of reunion would b nil; that seemed self-evident and hardly merited the attention th Author had given it. If, however, the by-pass or second channe had the effect of eliminating a washland flood the above conclusio would be unsound. Mr. Hillman included in his conception of a by pass, under his sub-heading "Embankment-Systems" (b), washlanc along which excess river-flow passed, and Mr. Farran though him wrong in dismissing that case. If such washland were t be replaced by a designed channel the effect on the flood-leve below the point of junction with the main river would be marke because of the elimination of the time formerly expended by th flood in spreading over the washland. Further, the relative length of the by-pass and the main river should be taken into accoun because a proportion of the flood peak might travel more rapidl down the by-pass than the remainder would down the river, o vice versa.

Mr. Farran agreed with Mr. Hillman that the effect of eliminatin the reservoir or washland area was, on a rising flood, to raise the floo stage below the point of re-entry of the by-pass. If, as might we be the case, the river at some point lower down flowed bank-fu under the original conditions, it would now cause a flood, and th banks would need to be raised at a considerable financial outlay

Mr. Farran.

The acceleration of the time of passing of the peak might be a great advantage, but on the other hand it might cause the main-river peak to coincide with a tributary peak, and so result in flooding many miles below the by-pass, possibly at a place where flooding had never before been experienced.

Mr. Farran found some difficulty in reconciling the figures given in Table I (p. 399) with those given in Table II (p. 407); for instance, on 24 May the discharge was given in Table I as 22,000 cusecs and the excess discharge to the reservoir as 13,000 cusecs, whilst in Table II at 1 a.m. on 24 May the discharge was given as 22,820 cusecs and the mean flow into the reservoir as 333 cusecs. If, as was stated in Table I, the bank-full discharge of the river was 9,000 cusecs whilst the excess discharge was 13,000 cusecs, surely the effect of eliminating the reservoir would be much greater than an increase in the flood-stage of 0·40 foot. He suggested, however, that Table I might be merely hypothetical.

The particular case discussed by Mr. Hillman, where the point of overflow and return of the flood water was the same, was not the most usual one. The case of the long washland which was filled at its upper end and returned water to the river at its lower end whilst at the same time the flood deepened and expanded, was more common. The computation of the capacity-curve of such an area would be a matter of complexity, and the comparison of readings taken at gauging stations above and below the washland, or reservoir, might give the same results with less labour.

Mr. Fawcett.

Mr. P. N. Fawcett, of Shanghai, was in entire agreement with Mr. Hillman. He concurred that the effect of a local improvement, such as a "cut-off" or series of "cut-offs," would not alter the total discharge; the effect of the "cut-offs" would be to create a higher velocity through the "cut-offs," and since the discharge remained constant at the figure it was before the "cut-offs" were made, the same volume of water would flow through the "cut-offs" in a smaller cross-sectional area, thus lowering the water-surface. Furthermore, the higher velocity would scour the bed of the "cut-offs," resulting in a further lowering of the water-planes, particularly in the "cut-off" channel.

He would draw attention to the experiments carried out in 1931 at the United States Waterways Experimental Station at Vicksburg, in the report [1] of which the following confirmatory statement would be found:—

"The model showed a maximum lowering of 2·2 ft. due to a cut-

[1] H. D. Vogel, "Application of Model Research to Mississippi Flood Problems," *Engineering News-Record*, vol. 107 (1931), p. 84.

Mr. Fawcett. off at Tarpley Neck, the influence being felt for a distance of 45 mile above with no change below. . . . The discharge, velocity and are of cross section below the cutoff remain the same, and hence th stage downstream is unchanged. Above the cutoff, velocities ar greater by reason of the increased slope and hence stages are lower."

He would also quote a later report [1] on large-scale models :—

" The larger model tests of seven cutoffs below the Greenvill bends were conducted individually and in combinations. Based o the tests of all ten cutoffs and with both models, the hydrauli findings can be summarized as follows :—

" Investigations conducted on the ten cutoffs lead generally to th conclusions that a lowering of stages will result in immediate upstrean reaches, while immediately below, except as lowered by the nex cutoff downstream, the stages will remain as before."

Mr. Lacey. Mr. J. M. Lacey observed that the problem of dealing with flood preventative works connected with a large river was always difficult A study of the Reports of the Mississippi River Commission [2] woul exemplify that statement. Mr. Hillman's Paper presumably deal only with the fluviatile section of a river, and with rivers in Grea Britain. " Cut-offs " in the lower sections or reaches of a river wer less violent and destructive than in the upper reaches, owing to th flatter slopes and more gentle current. It was obvious that " cut offs," if artificially carried out to improve the alignment of a river should begin from its mouth, and should be excavated during th season of normal flow in the river, so that the latter might have tim to adjust itself to its new channel. The river ought to be firml established in its new course before another " cut-off " was mad higher up the river. The alignment of the " straight-cut " or " cut off " should be in the direction the river would naturally and easil take, which was not an easy matter to determine. The vagaries of river were such that it would sometimes refuse to follow the path allotted to it, with the result that the " cut-off " would in tim silt up.

If the river had arrived at maturity, as most British rivers had and were subject to deposition in its lower reaches, the effect of th flood-banks would be to raise the flood-level and to reduce the surface slope in those reaches ; eventually, by continual deposition, th river would rise above the level of the adjacent country, and woul become a source of considerable danger. In the upper reaches

[1] " New Plans for the Mississippi : General Hydraulic Phenomena Studie with Models," *Engineering News-Record*, vol. 111 (1933), p. 41.

[2] D. O. Elliot, " The Improvement of the Lower Mississippi River for Floo Control and Navigation," U. S. Waterways Experiment Station, Vicksburg Miss., 1932.

Mr. Lacey.

where the gradients were steeper, and transportation was still in progress, the effect of such flood-banks might not be so serious. The general effect of flood-banks would be to alter the natural flow of a river, while on the other hand, external spills (where water in flood was allowed to overflow the river margins) did not disorganize stream-flow, for such spills left the stream in perfect order, and relieved it of an excess flow. There would not be the same objection to flood-banks if they were of moderate height, say 2 feet or so, and sufficiently consolidated to allow large floods to spill over them, very much on the principle adopted by Mr. F. A. Leete.[1] The cost of land would fix the distance those banks could be set back from the river margins. The late Mr. C. W. Merrifield, speaking in the Discussion on two Papers [2] at the Institution, had given further information.

The most rational way of enabling a river to carry off its floods was to remove all obstructions such as embankments, weirs, dams, locks or any works across or along a river which would obstruct its natural tendency to widen and deepen its section during floods; and to allow a free and uncontrolled passage of tidal flow up and down the river. That, however, would interfere with the amenities of the river and its use for navigation, so that some sort of compromise was generally necessary. The effect on the depletion of ground storage had also to be considered if the floods were passed off too quickly.

With regard to the section of the Paper dealing with the effect of by-pass-channel flow on flood-levels, a by-pass would be necessary only if an upper reach were liable to submersion, and as such was acting as a flood-moderator, as described on pp. 401 and 402; the effect of the by-pass channel would be to permit a sudden discharge into the lower reach of a larger quantity of water than before, and the engineer responsible for its execution would have some difficulty in proving that the effect of the by-pass was nil.

In the higher stage of the river the surface-slope would also have to be taken into consideration in obtaining the discharge-curve. Table II showed that, for nearly 8 hours from midnight, 23 May, to 8 a.m., 24 May, the water level was almost stationary. Had Mr. Hillman ascertained whether there was any obstruction in the river lower downstream? Such an obstruction might take the form of a bridge-opening, a contracted waterway or a paved crossing, which would cause that heading-up, and which, if removed or rectified,

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1 "The Regulation of Rivers without Embankments." London, 1924.

2 G. I. Symons, "On the Floods in England and Wales during 1875, and on Water Economy," and C. Greaves, "On Evaporation and on Percolation." Minutes of Proceedings Inst. C.E., vol. xlv (1875–76, Part III), pp. 1 and 19.

Mr. Lacey. might cause a reduction in flood-levels. Flood-levels some distances down the river might indicate if any such obstruction existed.

The frequency of great floods, and the cost of preventing or ameliorating inundations due to them so as to be commensurate with the resulting advantages, was one of the most difficult problems confronting the engineer.

Mr. Marsh. Mr. C. M. Marsh pointed out that the method of analysis of the flood-hydrograph, as given in Table II, p. 407, of Mr. Hillman's Paper, was first used in connection with the flood protection schemes at Colombo, Ceylon, on which he had been engaged for 3½ years under the late Mr. C. C. Harward, Assoc. M. Inst. C.E., the originator of the schemes, and later under Mr. Hillman. At Colombo the schemes had proved so successful as far as the lands inside the area were concerned that the owners and occupiers of the unprotected lands outside the flood-banks had clamoured for an extension of the schemes to include their areas. In particular, those in the area immediately upstream of the protected lands had strengthened their claim for protection by affirming that not only were their lands inundated to a greater extent than previously, but that the extra depth of flooding had been larger than that foretold by Mr. Harward. It was with the object of determining the extent of the increased flooding that the analysis had been devised, using as a base the hydrograph of the 1927 and subsequent floods and calculating from the curves the lower levels to which those floods would have risen if the storage-capacity of the protected areas had still been available. The result of the analysis had confirmed the predictions of Mr. Harward at almost every point.

In the case described in the Paper Mr. Hillman had had to tackle the reverse problem of determining the increase in future floods if the river were deprived of storage-capacity by carrying out the proposed Nottingham Flood Protection Scheme. The analysis was, however, fundamentally the same as that used at Colombo. Mr. Hillman had reached the conclusion that an increase of 0·4 foot might be anticipated. That figure was arrived at by the use of the discharge-curve (*Fig. 2*) for converting the discharge given in Table II (col. 8) into the levels given in Table II (col. 9), but that discharge-curve was the curve for the river-flow under its present conditions, and would not be applicable to the river after it had been embanked and deprived of storage. An examination of that curve showed that it rose uniformly from a river-level of 69 O.D. to a river-level of 77 O.D.; at that point, which presumably was where the storage-capacity of flooded lands was first utilized to any marked extent, the curve fell off fairly sharply. If that storage were no longer available and the river were confined to lands near its course, the discharge-curve

would probably continue as a straight line, or as a close approximation thereto, up to the level of the flood-banks. Revising the curve in accordance with that assumption, the maximum figure of 24,460 cusecs given in Table II (col. 8) would be converted into a river-height of about 81·3 O.D. and not into a height of 79·44 O.D., giving an anticipated rise of about 2·3 feet instead of the 0·4 foot given in the Paper. Mr. Marsh.

Mr. J. C. A. Roseveare, dealing first with the Paper on St. Germans Sluice and Pumping-Station, observed that on p. 381 Mr. Clark had mentioned that the Ministry of Agriculture and Fisheries had recommended the scheme for a grant to the Unemployment Grants Committee. The function of the Ministry had been to examine the scheme and, if satisfied, to certify it as a work of public utility. As the engineer responsible for advising the Ministry in such matters, Mr. Roseveare had had to consider the proposal in great detail. The proposal had been under consideration in 1926, before the setting up of Catchment Boards provided for under the Land Drainage Act of 1930. In consultation with the late Captain G. E. Mathews, Engineer of the Ouse Drainage Board, he had discussed the matter with Mr. Clark. When considering what effect pumping at St. Germans might have on the discharge of flood-waters from other drainage districts into the tidal Ouse, Captain Mathews and himself had come to the conclusion that, if large quantities of water were pumped into the tidal river at the period of low water during floods, the discharge from other districts would be prejudiced. Mr. Clark, however, naturally had to consider primarily his own drainage district, and, due to the continued neglect of the outfall of the Ouse and the heavy siltation which had taken place in the ⅜-mile length of channel between the sluice and the Ouse, the discharge capacity of the Middle Level Main Drain was becoming seriously deficient. In his Paper Mr. Clark had mentioned the wasting of the fen as a contributory factor, but in most cases he thought that that was already counteracted by increasing the lift of the smaller internal pumping stations of the area. Another very serious factor was the improvement which had taken place in recent years in the rate of discharge of the pumps belonging to those Boards. Certain observations which had been made during the recent floods had been mentioned, which appeared to indicate that temporary cessation of pumping at St. Germans caused an immediate drop in water-level in the main river, and therefore benefited other districts. There was, however, another side to that question. The "time of concentration" was an important factor in connection with floods, and, as it was undoubtedly a fact that the pumping plant at St. Germans was capable of discharging the flood-waters from the Middle Mr. Roseveare.

Mr. Roseveare. Level area probably some days earlier than would be possible by gravitation alone, the earlier discharge of the flood-waters from the Middle Level might be of some advantage to the whole system of the Ouse Catchment Board. An interesting feature in connection with the plant was that, due to the robust design and construction of the engines, they might be pressure-charged and run at higher speeds in order to discharge water against greater heads than at present contemplated. It would appear, therefore, that the Middle Level Board had a pumping plant which, if necessary, would be capable of pumping almost continuously throughout a spring-tide period. In Mr. Roseveare's opinion, any pumping which might be done at other than low-tide periods would be in no way harmful to other interests.

The Land Drainage Act provided that such a structure as that described in the Paper should not be constructed without the consent of the Catchment Board unless, as in the case under consideration, it had been begun before the commencement of the Act.

It had also been questioned whether the pumps were placed in the most advantageous position, and, apparently with the idea of suggesting that they were not so placed, the case of Sams' Cut had been quoted. There was no justification for comparing Sams' Cut and the Middle Level Main Drain. The Cut had been named after Dr. Sams, who was one of the adventurers associated with Vermuyden in draining the Bedford Level in the early part of the seventeenth century, and it discharged into the Ten Mile river above Denver Sluice. Judging by its state in 1924, it might have been assumed that it had never been deepened and widened since its formation! The installation of the second pump 4 miles from the outlet of that drain was obviously an ill-advised action on the part of the small drainage authority concerned, and the pump was practically never used. Owing to mismanagement of the drainage a large part of the area had become derelict, but in recent years, with the aid of grants from the Ministry, the drainage had been rearranged to lead towards a new pump on the banks of the river Wissey.

Practically the only alternative site for the Middle Level pumping station would have been at the aqueduct, 8 miles upstream of the outfall of the drain into the Ouse. That appeared to be a convenient site, as there was an existing restriction of the main drain at that spot, and it was nearer the danger zones in the Middle Level as well as being not very far downstream of the junction of several large drains. He had suggested that site to Mr. Clark when the matter was first under consideration, but Mr. Clark had pointed out several disadvantages, one of which was that he would obtain no positive discharge against tidal levels except in so far as he could surcharge

Mr. Roseveare.

the $7\frac{1}{2}$ miles of Main Drain between the aqueduct and St. Germans sluice. That length of drain ran through land which was entirely outside the Middle Level's jurisdiction, and the authorities concerned in those areas objected to any artificial raising of the water-level in the Main Drain. Another disadvantage was that it was usually advisable to lower the water in the drains in anticipation of flood. If the pumps had been situated at the aqueduct that would mean that water-levels would have been unduly lowered in the drains where they were used for navigation, which might have led to difficulties with navigation interests. As there had been great uncertainty as to whether the outfall of the Ouse would be improved within a reasonable time, and in view of the great improvement which was continuously being made in the drains of the Middle Level system leading to the outfall at St. Germans, it had finally been decided to locate the pumps in the old part of the Main Drain, as indicated in Fig. 1, Plate 1. On application by the Middle Level Commissioners to the Unemployment Grants Committee, the Ministry had therefore been able to certify the scheme as a work of public utility.

Mr. Clark was to be congratulated on having completed the work in ample time for the floods which had occurred during the 4 months ending in February, which in the Ouse area had been the most serious since that of January, 1928. Mr. Roseveare hoped that Mr. Clark would be able to embody in his reply particulars of the successful drainage of the Middle Level during the recent anxious period.

Mr. Hillman's Paper was an excellent example of the investigation necessary before large flood-relief works were undertaken. The paragraphs dealing with the use of reservoirs for flood-relief purposes were of great interest, particularly so in view of proposals which had been put forward from certain irresponsible quarters for the construction of reservoirs as an alternative to river-improvement works. It was clearly demonstrated in the Paper that such reservoirs would need to be of such enormous size that they would be entirely impracticable for the purpose suggested. The siting of such proposed reservoirs was a very important item in connection with any such scheme, and he had suggested in a recent Paper[1] that, although the two large reservoirs of the Derwent Valley Water Board on the upper reaches of the river Derwent had undoubtedly reduced the peak of the flood in the Derwent below the reservoirs, it was probable that the retardation of the flood in that river had caused it to coincide with the peak period of flood in the river Trent at Nottingham.

An outstanding example of the construction of flood-relief reservoirs

[1] "Land Drainage in England & Wales." Trans. Inst. W.E., vol. xxxvii 1932), p. 178.

Mr. Roseveare. was that of the flood-protection works of the Miami Valley, Ohio, U.S.A. Those works had cost about £7,000,000 and had been constructed following a most exhaustive investigation after the great flood of March, 1913. The catchment area dealt with amounted to 2,560,000 acres, which closely compared with that of the Thames above Teddington, namely, approximately 2,459,000 acres, and to a lesser degree that of the Trent above Wilford, 1,782,470 acres. It was estimated that 7·27 inches of rain from the whole catchment area ran off in 3 days in the March, 1913, flood and the scheme was designed to deal with 40 per cent. more than that figure. It had been found necessary to site the reservoirs as close as possible to the area to be protected from flooding, and seven reservoirs had been constructed having a capacity of 841,000 acre-feet. The reservoirs were retarding basins only, from which the discharge was not alterable but varied according to the height of water in the reservoir. The important point to be remembered in connection with the Miami scheme was that the retarding basins were only one feature of the scheme, which consisted also of very large river-improvement works.

As Mr. Hillman had showed, the period of the flood was the important factor, and when the extended period of the recent floods in Great Britain was considered it was quite impossible to suppose that the construction of reservoirs alone would give reasonably beneficial results. Uncontrolled reservoirs, or "washes" as they were called in the Fens, were a well-known feature of Vermuyden's drainage works. The largest in Great Britain was the Washland storage available for floods on the Ouse, and it might be of interest to record that it was now possible to control the run-off from that wash due to the construction of the new Welmore lake sluice in 1931.

Mr. Hillman drew two conclusions on p. 409, but it was essential to consider them together, as the first proposition would not arise unless the result was to eliminate storage-capacity; Mr. Hillman agreed that that was the case in his statement on p. 409. Unless provision were first made for that by works in the lower reaches of the river, Mr. Roseveare thought that the carrying out of the upper works was inadvisable, as, should any undue flooding occur or embankment fail in the river below that improved, the Catchment Board might receive claims for compensation. It was admitted that any such claim would be hard to substantiate, but nevertheless it might cause great inconvenience to the Board. He had recently heard of a case where farmers had threatened such action following a breach in an embankment, alleging that work had been carried out in upper reaches of the river before improvements in the lower river had been undertaken.

Mr. J. M. B. Stuart observed that he was interested in Mr. Hillman's Paper, as the Author had dealt with a question which Mr. Stuart had encountered on several occasions during work in Burma. Mr. Stuart.

Mr. Hillman had stated that flood-protection works might usually be divided into two categories :—

(1) Channel-improvement or by-passing, with the object of reducing flood-levels locally.

(2) Embankment systems, with the object of excluding flood-waters from certain areas.

Mr. Stuart would add a third category; namely, flood-detention reservoirs which held up the peaks of floods and reduced flood-levels downstream; Mr. Hillman had referred to that form of reservoir on pp. 398 and 399. The questions Mr. Stuart had had to deal with were :—

(*a*) The construction of embankments to rivers in order to protect cultivated land against flooding. In that case the problem was to find the increased levels to which the river would rise when any spilling over the banks was prevented, as in Mr. Hillman's example at Nottingham.

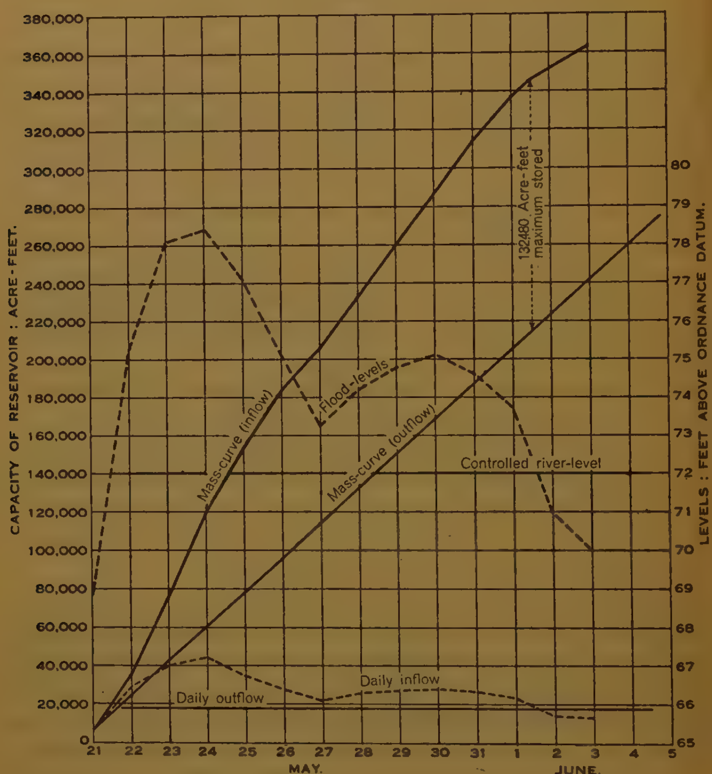
(*b*) The construction of detention-reservoirs in the head-waters of a river in order to hold up floods, and so reduce flood-levels in the lower reaches. The problem was the reverse of (*a*), and was to find to what extent a reservoir of given capacity would reduce flood-levels, or to find the reservoir-capacity necessary to keep floods in the river down to certain maximum levels.

Mr. Hillman, on pp. 398 and 399, had referred to controlled and uncontrolled reservoirs; Mr. Stuart agreed with him that controlled reservoirs made the most efficient use of the available capacity if they were kept empty until a flood came down, and were then only utilized when the discharge in the river exceeded the safe maximum. It was wasting the absorptive-capacity to let water into the reservoir as long as the river could safely take the discharge. The works which were required for such control were expensive and required the maintenance of staff on the site to work them, and it was preferable, especially in tropical countries where the head-reaches of rivers were far removed from civilization, to have some form of works that operated automatically.

Uncontrolled reservoirs had been adopted in the Miami Conservancy District in the United States, and he understood that they had worked satisfactorily. Flood-detention reservoirs built across the

Mr. Stuart. valleys in the upper reaches of the rivers held up the peaks of floods, the water being discharged through an outlet designed to limit the river-discharges to safe dimensions. Those reservoirs were quite automatic in their action and their beds were dry until a flood came down. He thought that Mr. Hillman had been fortunate in having very complete records of flood-levels and discharges; the engineer overseas had to design his schemes on much less information, as in all

Fig. 7.



probability gauge-readings once a day and a few measured discharge would be all that he would have on which to base his calculations. I problems of that nature it was very important to calculate a accurately as possible the probable maximum flood, and in uncivilize countries, where gauge-readings for a limited number of years onl were available, the engineer was compelled to resort to assumption The measurements of the discharge and duration of a flood wer generally available for use as a basis, and those figures were multiplie

by a factor which depended on local conditions, such as high flood-levels in the past. In dealing with those problems he had found the use of mass-curves to be of great assistance. Mr. Stuart.

The mass-curves from the figures given in Table I of the Paper were shown in *Fig. 7*, and from them he had determined that the reservoir-capacity would have to be 132,480 acre-feet. The figures were set out in Table A:—

TABLE A.

Figures for Mass-Curves compiled from Table I, p. 399.

Date.	Daily inflow: acre-feet.	Mass inflow: acre-feet.	Daily outflow: acre-feet.	Mass outflow: acre-feet.
May 21	7,200	7,200	7,200	7,200
22	29,320	36,520	18,000	25,200
23	40,240	76,760	18,000	43,200
24	44,000	120,760	18,000	61,200
25	35,320	156,080	18,000	79,200
26	28,400	184,480	18,000	97,200
27	22,000	206,480	18,000	115,200
28	25,800	232,280	18,000	133,200
29	27,400	259,680	18,000	151,200
30	28,000	287,680	18,000	169,200
31	26,800	314,480	18,000	187,200
June 1	23,200	337,680	18,000	205,200
2	14,400	352,080	18,000	223,200
3	11,800	363,880	18,000	241,200
Total . .	363,880	—	241,200	—

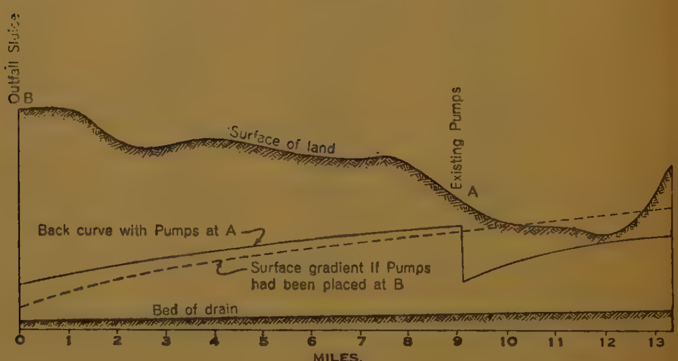
The inflow mass-discharges in acre-feet were plotted against the days of duration of the floods, as was shown by the upper curve in *Fig. 7*; the river-discharge was limited to a maximum of 9,000 cusecs, and the daily discharge was constant, so the outflow mass-curve became a straight line. The maximum ordinate between the two lines represented the maximum storage-capacity required, and from the curve showing the reservoir-capacity the maximum flood-level could be determined. That was a simple example; in more complicated cases, however, where only the inflow mass-curve was known and it was desired to determine the effect of a channel, in which the discharge varied with the depth, on the amount of storage required, Mr. Stuart thought that the mass-curve method was almost essential.

In an example of that type the mass-curve for the outflow would have to be obtained by a method of trial and error, by balancing the outflow during the period against the storage at the end of the period until, for the same gauge-reading, the outflow plus the storage equalled the mass-inflow.

Mr. Stuart. The daily inflow and outflow and the corresponding water-leve could also be plotted on the same graph, so that a graphic record the rise and fall of the flood would be obtained in a convenie form.

Mr. Tomes. Mr. F. H. Tomes observed that there was no doubt that, in th Witham catchment area, many fen pumps were wrongly placed the extreme outfall end of long, wide and shallow drains, and tha it was not uncommon that plants so placed had to cease pump ing at intervals because the drains were unable to convey th water at the same rate that the pumps could deal with it. Th hydraulic mean depth in a drain of that type had a low value an the back-surface gradient from the pump took the form of a paraboli curve rising steeply from the intake sump, with the result that at surprisingly short distance upstream the surface-level coincided wit

Fig. 8.



that which would have obtained had the pump not been operating an the drain discharging by gravity. The calculation of that bac curve was necessarily laborious, because the drains varied in sectio from point to point, and, although there were other methods, h found it best to calculate the length of the drain for each inch rise o surface-level. That method had proved reasonably accurate in case where the results had been checked.

As in the case of the Middle Level, many of the pumps in th Witham Fens were situated on comparatively high ground at th outfall end of the drain, whilst the low lands subject to flood wer some distance "inland." In the case of the East Fen the low lan lay at O.D. at between 10 and 13 miles from the outfall sluice (*Fig. 8*) The pumping station had not been erected at the outfall, but at th point A, where sluice doors were built across the drain. Had th pump been erected at the outfall, B, the surface-gradient would hav

taken the form shown by the dotted line, and it was probable that the low land could not have been kept free from inundation, as at present. As, however, the pumps were at A the parabolic curve had its lowest point near to the low land, and the back curve took the form shown. An additional advantage was that the raising of the level on the down-stream side of the dam induced a surface-gradient towards the outfall very much in excess of that which would be obtained by gravity discharge, for it would be seen that there was very little bed-gradient in the drain. That tended to reduce the tide-locked period, as the 9-mile reach between the pumps and the outfall formed a valuable storage-reservoir. Only on one or two occasions had the pumps had to be temporarily stopped by reason of the reservoir having been filled to capacity. Another advantage arising from that reservoir was that the pumping could be continued during the tide-locked period against a small lift. In that case the reservoir capacity was so large, the surface area being about 100 acres, that the maximum lift was about 5 feet, whereas a pump at the outfall sluice would have had a lift of about 20 feet against the high-water level of ordinary spring tides. The machinery consisted of two pairs of high-pressure condensing vertical direct-acting steam engines of 240 aggregate nominal horsepower, driving pumps of the turbine type, one to each engine, 7 feet in diameter. The total discharge was 700 tons per minute and the area of land pumped was 35,000 acres. Mr. Tomes.

Mr. Clark, in reply, pointed out that the vertical staunching-bars for the sluice gates at St. Germans were not covered by rubber, but were ordinary turned round bars. The percentage of leakage varied each tide and was due to weeds, etc., clinging to the bars; on some tides the gates were perfectly watertight, but at other times slight leakage occurred. The lintel joint was made of rubber, and Mr. Clark's experience, based on similar gates and conditions, was that such rubber, even after 12 years' use, was in perfectly good condition. The total cost of the St. Germans installation was £224,000, the plant, including the sluice-gates and steel superstructure, costing about £75,000. The fact that the nearest railway siding was 4 miles away and that unemployed men had to be trained for the work were factors which, as Mr. Dean would appreciate, added to the cost. Mr. Clark.

The reinforced-concrete raft over the piles was introduced in order to distribute the dead and live loads. It would be observed that, as far as the dead loads were concerned, they were not equally distributed. The live loads were in the centre of the structure and occurred when the sluiceways were full or empty; each sluiceway had a capacity of about 1,000 tons, and each pump held 65 tons of water when full. The 12 feet of concrete was necessary above the raft in order that the suction-pipes of the No. 2 pump could pass

Mr. Clark. under the foundations of the No. 1 engine. At the same time the pumps depended on the supporting concrete up to within about 3 feet of the impeller-shaft centre-line. The mass concrete below the raft had been carried down lower than originally intended after the reinforced-concrete piles had been driven. The set of the piles had been specified as a total set of 1½ inch for thirty blows with a 2-ton hammer and a 3-foot drop, but in all cases the piles had been driven to a set at least 50 per cent. better than that. The "much more severe test" referred to by Mr. Clark in connection with the piles that had lifted was sixty blows with the same hammer and drop, and the set was about ¾ inch. Great care had been taken not only in making the links for the piles standard, but also in making the side straight. Further, in building up the cage for the pile, the main reinforcing bars were tight against the links. The cast-iron diagonal struts were inserted by means of a small jack. It had been his experience in work of that nature over the last 30 years that in some cases there had been as much as ¼ inch between the links and the main bars, resulting in shattered heads.

The piles were made of "Ferrocrete" cement, and at 5 days the question of handling and transporting them without developing cracks arose, as well as that of driving. In-situ piles were not considered suitable for the work and he recollected having seen piles of that nature driven in the lower reaches of the Thames over 20 years ago. The piles were supposed to have been about 15 inches in diameter, but after some time they had been uncovered and had revealed a series of corrugations varying from 15 inches to 10 inches in diameter, with the reinforcement all bunched together on the neutral axis; in fact such piles required a large factor of safety, and might not be considered to be suitable or reliable in all cases. The side walls of the outfall channel were reinforced, and in fact they might be considered as a channel-iron section taken in conjunction with the floor. The low-water tide-mark rarely exposed the top of the wall. So far, no movement had been observed.

He agreed that the floor and foundations were of a heavy character, but he considered that to be justified in view of the 1862 disaster and the conditions at the site.

If the estuary of the river Ouse had been reconditioned (and providing that the low-water neap tides had been lowered 5 feet as a result of such work), the erection of the pumping-station at St. Germans could have been delayed for some years. At the same time Mr. Farran was doubtless aware that the estimated cost of reconditioning the tidal portion of the river Ouse was of the order of £5,000,000. The annual maintenance-charges would have to be added to that figure. As had already been pointed out, for the last

100 years the Middle Level had been spending large sums in order Mr. Clark. to improve their drainage by gravitation. Raising banks and setting them back in order to increase storage-capacity would be expensive, as often the waterways were flanked by a road and houses—in some cases by roads and houses on both sides. Further, the question of bridges over those waterways had to be considered, and he feared that the cost in that case would be prohibitive. The pumps at St. Germans operated in flood-periods and in anticipation of floods. It might be of interest to mention that, during the winter from 1 November, 1935, to 28 March, 1936, the whole of the water was pumped out of the Middle Level at St. Germans with a total of 1,830 pump-hours. The water-level at March was maintained approximately at about low-water tide-level at St. Germans.

It was true to say that the farmers had already a heavy drainage rate to pay, which naturally varied in the minor internal districts. They had to pay more to the Middle Level for the St. Germans pumping-station, but on the other hand the internal rate was lower. On balance, Mr. Clark considered that the farmers paid somewhat less, and the following example had recently been brought to his notice, the internal district being 20 miles from St. Germans :—

In 1928, the cost of pumping was £337
,, 1936, ,, ,, ,, £154.

It was true that the 1936 flood was not so severe as that of 1928, but on the other hand, the boilers in that particular internal district had deteriorated so much that during the present year they had been condemned.

The relative merits of gravitation and pumps would have to be determined by a consideration of the conditions in each area. The cost ought not to be the deciding factor, as it was quite possible that farmers were able to farm more profitably on a pumped area which was drained and fertile than on a gravitation system which was waterlogged and at the mercy of floods, winds and tides. As stated by Mr. Roseveare, the decision to erect the pumping-station at St. Germans had not been arrived at without considering the effects both inside the Level and in the river Ouse. He would like to take the opportunity of expressing his appreciation of the help and assistance he had received, both from the late Capt. G. E. Mathews, Engineer to the River Ouse Catchment Board, also to Mr. J. C. A. Roseveare, Chief Engineer to the Ministry of Agriculture and Fisheries.

He claimed that the plant at St. Germans assisted the River Ouse Catchment Board by spreading its discharge over a longer period each tide. It would be appreciated that the question of navigation in the waterways above Upwell was a factor to be considered in

Mr. Clark. selecting the site for the pumping-station. Further, the cost of reconstructing twelve bridges 100 feet long with approaches having workable gradients, together with the lengthening of culverts under the main drain, had also to be taken into consideration. The raising of banks, together with the purchase of land at about £100 per acre, and last, but not least, the difficulty of keeping those banks watertight after a lengthly period of dry weather, ought not to be overlooked.

Generally speaking, the flood-level of 1935–1936 had been kept 5 feet 6 inches lower at March (17 miles from St. Germans) than the flood of 1928. At Whittlesey Mere, about 35 miles from St. Germans, it had been about 4 feet 6 inches lower. During the summer flood of July, 1936, the results had been about the same.

In the Middle Level, the majority of the pumps were situated on low ground farthest from the outfall. From Mr. Tomes' remarks it appeared that in the Witham Fens the conditions were not exactly the same. From *Fig. 8* (p. 642) it appeared that navigation was a factor that did not occur, so that the problem was simplified. At the same time, it would appear that the land on the suction side of the pump gained the advantage at the cost of land on the discharge side. Mr. Clark had seen more than one installation of that type with land flooded both on the suction and discharge sides of the pump. The deciding factors were the storage capacity between the outfall sluice and the pumps A (*Fig. 8*, p. 642), and more particularly the level of the discharge-water at the sluice compared with tidal ranges under flood-conditions, together with the time element.

Mr. Hillman. Mr. Hillman, in reply, appreciated the difficulty that a few correspondents appeared to have had in fully grasping all that was involved in the Paper, especially as he had not described the proposed Nottingham Flood Protection Scheme in detail; the scheme had not yet been officially sanctioned, and it was not considered desirable that certain information should be published at present. Briefly, it was proposed to protect certain low-lying urban lands to the south-west of Nottingham by means of flood-embankments. The effect, however, of eliminating both the storage-capacity and the washland flow over that land would be to increase flooding in the river and over unprotected areas adjacent and above. For various reasons it was impracticable to remedy that increased flooding by improving the river-channel adjacent to the embankment-system, but it was possible to increase the surface-slope of the river by means of a by-pass channel which would take off from the river about a mile below the embanked area. The drop in flood-level due to the by-pass channel was calculated to be somewhat in excess of the increased depth due to the embankment-system, with the object of ensuring

that unprotected areas should not suffer as a result of the scheme. Mr. Hillman. In addition to counteracting the adverse effect of the embankment-system, the by-pass channel would also cause a local reduction in flood-level of about 4 feet.

The purpose of the Paper had been to indicate a method whereby the total effect of both storage-elimination and by-pass-flow on flood-levels *below* the scheme might be studied. The word " below " had been emphasized, as one or two correspondents would appear to have missed that point. In that connection he thanked Mr. Fawcett for the quotations from American reports which so amply supported the contention that, except under special circumstances referred to in his reply to the Discussion [1], the effect of a by-pass channel on flood-levels below would be nil. The subsidiary effect of a by-pass channel in reducing storage-capacity was naturally taken into account, and had formed the main subject-matter of the Paper.

Referring to Mr. Farran's difficulty in reconciling figures, the reservoir referred to in Table I (p. 399) was purely hypothetical, and had been introduced for the reason explained in the Paper. The " reservoir " to which the figures in Table II (pp. 407 and 408) applied was the storage-capacity which, if the scheme were to be carried out, would be eliminated owing to the effect of the embankment in preventing the access of flood-water to one area, and the by-pass channel in reducing flood-levels elsewhere. The flooding certainly did not all take place from one spot designated in the Paper as " the junction," but as far as the effects on flood-levels below the scheme were concerned, it was immaterial as to exactly how the flooding occurred. The important features were the volume of storage eliminated and the shape of the hydrograph. The conception of " the junction " had been introduced in the Paper in an attempt to clarify the issue, and to enable a clear conception to be grasped of the different effects of moving and ponded water. Those effects had been purposely separated in the arguments submitted, but, as Mr. Roseveare had emphasized, it was essential to consider the combined effects of both when such schemes were under investigation.

Mr. Lacey cited the late Mr. Merrifield's suggestion that the most rational way of enabling a river to carry off its floods was to remove all obstructions such as weirs, dams, and locks. While by no means disputing the advantages of clearing obstructions, Mr. Hillman submitted that the conception that flooding could be totally prevented by such means was fundamentally unsound. In the Paper,

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[1] p. 438 *et seq.*

Mr. Hillman. and in the subsequent discussion, it had been shown that natural scour provided and maintained a channel which was capable of accommodating, bank-full, perhaps one-third of the discharge that might flow down a valley during a high flood. Merely clearing that natural channel would not enable it to carry the extra two-thirds. He did not wish to be exact on the figure of one-third, as the ratio of bank-full to maximum-flood flow varied according to circumstances. The ratio of one-third, however, appeared to be about correct for alluvial rivers of the size of the Trent or Thames, both in England and in the tropics. The question was of great importance, and merited further examination.

Mr. Lacey also suggested that the effect of the by-pass channel would be to permit the sudden discharge into the lower reach of a larger quantity of water than before. That, however, would only be the case if the by-pass were to be kept closed until considerable ponding had occurred above. It might be mentioned that it was proposed to control the by-pass channel by means of automatic sluices, the object being twofold; firstly, during normal times it was necessary to maintain a certain level in the river for navigation purposes, and secondly, it was not considered desirable that flow should take place in the by-pass channel except during floods. The reason for that was that if continual flow were to be permitted in the by-pass channel, both river and by-pass (particularly the latter) would tend to silt up. As soon as the river rose above a predetermined level, the by-pass sluices would partially open, the flow being automatically regulated according to requirements. Provision would also be made for manual operation of the gates for the purpose of preventing stagnation in the by-pass channel.

Mr. Marsh, to whom Mr. Hillman was greatly indebted for his assistance in Colombo when the method was being developed, suggested that the discharge-curve (*Fig. 2*, p. 404) was the curve for the river under its present conditions, and would not be applicable to the river after it had been embanked and deprived of storage. That would be perfectly true if the improvements included banking at the particular point to which the discharge curve referred, but it would have to be remembered that the investigations were confined to the effect below the scheme, at a point where the flood-channel was not to be altered in any way whatever, either in slope or cross section. The discharge-curve would therefore be exactly the same both prior to and subsequent to the carrying out of the scheme. An alteration in storage-capacity above would alter the discharge but not the discharge-curve.

Paper No. 5056.[1]

"The Construction of the Mersey Tunnel."

By David Anderson, B.Sc., M. Inst. C.E.

Correspondence.

Mr. J. I. Graham observed that it was not generally realized that the proportion of carbon monoxide present in the exhaust gases of petrol-driven cars was as much as, or sometimes more than, 6 per cent. When that was understood, the danger of running the engine in a confined space such as a closed garage would be obvious. The inhalation of an atmosphere containing 1 per cent. of carbon monoxide, but having plenty of oxygen and being otherwise respirable, would be followed by insensibility after about 1 minute if hard work were being carried out, or in about 3 minutes if resting, whilst 0·3 per cent. would produce unconsciousness in about 5 minutes during work or 15 minutes if the subject were at rest. In an atmosphere containing 0·12 per cent., 45 minutes would produce disablement where hard work was being carried out, whereas at rest disablement would take place after about 2 hours. Even with 0·04 per cent., headache and discomfort would be evident after 45 minutes of hard work, and 0·02 per cent. would be responsible for headache in some cases after a couple of hours. In a recent Paper [2] the late Professor J. S. Haldane had discussed the physiological effects of small quantities of carbon monoxide, and showed why a limit of 0·025 per cent. was fixed for the carbon monoxide concentration. In that Paper he drew attention to the recent work of Dr. Esther Killick on acclimatization to a small concentration of carbon monoxide, a matter obviously of great importance to patrols and other people who had to be in the tunnel for a prolonged period. Dr. Killick had shown that acclimatization to, say, 0·02 per cent. might be such that the blood of the acclimatized person might only be saturated to less than two-thirds of the saturation of someone unacclimatized. Mr. Graham.

Valuable data had been published in a report [3] by the U.S. Bureau of Mines, which included many analyses of exhaust gases and figures for the production of carbon monoxide in cubic feet per hour. Owing

[1] p. 473 (April).

[2] "The Ventilation of Tunnels," Journal Inst. Heat. and Vent. E., vol. 4 (No. 37, 1936), p. 18.

[3] Report of the New York State Bridge and Tunnel Commission to the Governor and Legislature of the State of New York, 1921. Appendix No. 3, p. 91.

Mr. Graham. to the, in general, somewhat larger petrol-consumption of American cars compared with cars in Great Britain, it seemed probable that the figures for carbon-monoxide production given in that report were higher than the average production in Great Britain, apart from the question of vehicles fitted with diesel engines. As the Author had pointed out, the assumption that 1·5 cubic foot of carbon monoxide was emitted per minute per car was no doubt distinctly high. The authorities responsible for the control of the ventilation of the Holland tunnel had first fixed a limit of 0·04 per cent. of carbon monoxide, but when, at the request of the engineers of the Mersey tunnel, he had visited the Holland tunnel, he had been told that a lower limit had had to be arranged largely owing to the nuisance from mist and impaired visibility. Even with 0·025 per cent. the visibility had been reduced as a result of the suspended matter and condensing moisture expelled from the exhausts. The carbon-monoxide recorders installed in the Mersey tunnel ventilation-buildings were, in general, much the same as those fitted in the Holland tunnel, for the design of which Dr. S. H. Katz was responsible. The measurement of the carbon monoxide depended, as the Author had stated, on the oxidation of the carbon monoxide to carbon dioxide in the presence of a catalyst, which was a mixture of specially-prepared copper oxide and manganese dioxide. By means of a series of thermocouples arranged differentially, the heat of oxidation was indicated or recorded on instruments calibrated directly in parts of carbon monoxide per 10,000. For the plant to function satisfactorily it was essential for the air under test which was passing to the catalyst chambers to be very efficiently dried. In the original plant that had been done by passage through concentrated sulphuric acid, but as a result of a long series of tests in the Mining Research Laboratory at Birmingham, and in conjunction with the Kestner Evaporator Company and the Cambridge Instrument Company (who had been responsible for the production of the analysers and recording apparatus), a double-unit silica-gel drying plant had been supplied for each analyser. That method of drying the air had, he believed, resulted in a longer life for the catalyst, and was undoubtedly very much simpler from the point of view of operating the plant. The air under test was dried to a moisture content of under 0·01 grain per cubic foot.

The Author had pointed out that at the present time the carbon-monoxide content did not normally exceed one part in 10,000. Owing to the larger diameter of the Mersey tunnel the effect of a slight fog was, he thought, more apparent than a mist of similar concentration in the smaller Holland tunnel. At 0·01 per cent. of carbon monoxide the mist or fog, although appreciable, did not

interfere with driving in the slightest. It was, however, interesting to consider the effect of an increase in the number of diesel-engined vehicles. In his opinion, unless means were taken to remove the suspended matter from the exhaust of such vehicles the fog formed would be almost more objectionable than the vitiation of the atmosphere by carbon monoxide. He had tested the exhaust gases from a number of diesel engines, more particularly those designed for use as mine locomotives, and as a rule he had found that, as compared with petrol engines, only about one-tenth the quantity of carbon monoxide was formed, and even less when the engine was running efficiently under full load. Mr. Graham.

Another matter connected with the construction of the tunnel, and one which was, he thought, of interest, was the possibility of the production of a harmful atmosphere during cement-proofing through the production of finely-divided silica. He had investigated that possibility at the request of the late Professor J. S. Haldane, and had found that the very fine dust, which was of particle size less than 10 microns, suspended in the air during that operation had consisted practically all of cement-dust, the free silica forming under 1 per cent. There was thus no danger of workmen developing silicosis in such operations.

Professor DOUGLAS HAY pointed out that attention had already been drawn to the considerable part played by the ventilation-system in the design and construction of the Mersey tunnel. It was inevitable that the newness of the problem should have brought many anxious moments to the engineers responsible, whilst the great dimensions and layout of the tunnel made the problem more difficult. It had been wisely decided to await the opening of the Holland tunnel and to profit as far as possible by the experience that would then become available, but even so the essential differences between a pair of one-way tunnels and a single tunnel of large diameter had left a problem requiring careful examination. The decision to complete as rapidly as possible a 1,000-foot section of the tunnel under Hamilton square and to carry out therein full-scale tests had made it possible to arrive at a complete solution. By dint of hard work on the part of all concerned, little or no delay had resulted before the tunnel was opened for traffic. In carrying out the experiments at Hamilton street three issues presented themselves. Firstly, the proper manner of coursing the air-currents through the traffic space had to be determined. Secondly, the most efficient method of admitting air into the traffic-space had to be found; and, thirdly, it was necessary to discover what was the best type of ventilating fan to use. Professor Hay.

Under the first heading the principal question had been as to whether or not the full transverse system, with top ceiling-duct,

Professor Hay. used in the Holland tunnel was essential or desirable at Liverpool. The upper duct made no difference to the dilution of noxious gases obtained with a given fresh-air admission; it spoilt the appearance of the tunnel, was costly to build, and required considerably more power in use. At Liverpool an additional annual cost of about £4,000 a year for electricity would have been entailed. It appeared to have some advantages in case of fire, but in a large-diameter tunnel those advantages were not so apparent. The decision had therefore been taken to omit the ceiling-duct, and experience gained during the past 18 months had confirmed the wisdom of that step. It was, in fact, doubtful whether its use was justified even in a small-diameter tunnel.

With regard to the second point, experiments had been carried out at Hamilton street to determine the best design of air-admission slot through the road-deck; various model slots had been set up in lengths, and the resulting mode of air-admission tested, until an even and smooth flow of air had finally been obtained. Pressure losses in the air-ducts and slots and at bends had been measured, and as a result modifications had been made in the duct-system to reduce losses to a minimum. It was rarely realized how much power could be lost at a badly-designed bend. Actual losses of 80 horse-power at a single right-angled bend had been measured under full-quantity conditions, so that the care taken in streamlining bends wherever possible was fully justified.

Finally, it had been a cause of great regret that the compact type of axial-flow or propeller fan had proved to be too inefficient and noisy. At the time the tunnel had been built the design of such fans had been in too early a stage for commercial adoption on the large scale required; since the opening of the tunnel, however, design had proceeded rapidly and commercial experience had been gained, and in future tunnels the propeller fan would demand consideration. Its adoption would effect large savings in the building space and duct-system required.

The care taken in considering the design of the ventilation-system and the costly experiments made had, however, justified themselves by the results. The ventilation-system had given no trouble, and its maintenance over a period of years ought to be low. The experience gained at Liverpool would be of great advantage in the design and construction of future tunnels; it was likely that the road tunnel might prove popular in the future, not only in solving cross-river-transport problems but for meeting land-transport problems in densely-populated areas.

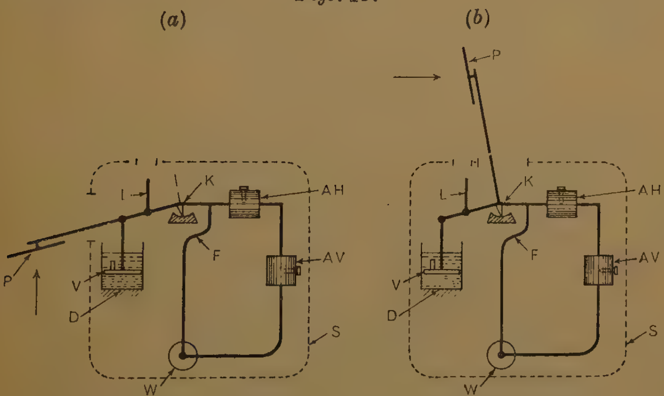
Mr. Hodgson. Mr. J. L. Hodgson observed that the meters he had designed for measuring the air-flows in the various ventilation-ducts of the tunnel

Mr. Hodgson.

were similar to those which he had previously designed for measuring the ventilation-air in the ducts of the Mount Victoria tunnel in New Zealand. In the case of the Mersey tunnel, the air-flow was measured at sixteen points in the ducts, indicated electrically in the six fan-control rooms, and recorded electrically in the central control room.

The meters were of the impact-plate weight-controlled type. Movements of the arm carrying the impact-plate operated an electrical potentiometer to which the indicating and recording instruments were connected. The range of accurate flow-measurement was 1 to 5. The size of impact-plate used varied with the maximum air-velocity to be measured so as to ensure approximately the same operating force at the same fraction of full flow in all cases. The maximum force on the plate was about 1 lb. Five sizes of plate,

Figs. 15.



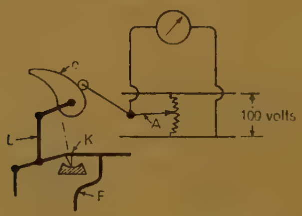
ALTERNATIVE TYPES OF IMPACT-PLATE TRANSMITTERS.

ranging from $8\frac{1}{2}$ inches to 17 inches in diameter, were used to cover a range of maximum air-velocities varying from 15 to 60 feet per second. The impact-plate type of meter was used in preference to a Pitot tube and an oil-sealed bell on account of the ease with which it enabled the low air-velocities to be measured with accuracy. (The Pitot head corresponding to an air-velocity of 3 feet per second was only about $\frac{1}{500}$ inch of water, whereas the force on an impact-plate was about $\frac{1}{25}$ lb.)

There were two designs of the impact-plate transmitters, one for the vertical and the other for the horizontal ducts, as illustrated diagrammatically in *Figs. 15.* P was the impact-plate, W was the pendulum-weight, AH and AV were the horizontal and vertical adjustment-weights respectively, and K was a knife-edge on which the frame F carrying the above parts operated. The contact-surfaces of the knife-edge and its bearing were covered with mercury

Mr. Hodgson. (not shown) in order to keep them free from grit and dust. A valve V enabled the damping of the dashpot D to be readily adjusted. The whole of the mechanism was enclosed in a metal shield S. The arm carrying the impact-plate projected through a slot in the shield, and its angular movement was about 11 degrees on either side of the mean position. The variation of the flow-coefficient of the plate with angularity of presentation, and with the VDW/μ value of the plate and duct, was allowed for on the cam C shown in *Fig. 16*. The cam, which was connected to the frame F by the link L, operated a potentiometer arm A, and the cam and potentiometer were enclosed in a dust-tight box. The electrical circuit for the non-summation instruments was shown in *Fig. 16*. A voltage-controlled motor-generator maintained a constant difference of potential across the terminals of the bus-bars to which each of the indicating and recording instruments were connected. The use of the variable

Fig. 16.



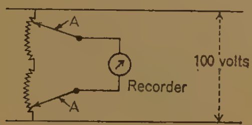
POTENTIOMETER AND CONNECTIONS.

pendulum-weight W enabled larger plates to be used at the higher maximum velocities than would otherwise have been possible. It was desirable to have as large plates as possible at the high velocities in order to ensure that the "impact" forces depended upon the size of plate in use, rather than upon the air-resistance of the arm to which the plate was fixed.

When installing the meters, many new problems had to be faced, as the flows had to be metered both immediately after bends and immediately after fan-outlets. The general method adopted had been to choose from the drawings those measuring stations which seemed to be most suitable, and then to check the positions by actual inspection of the sites. Removable Pitot tubes on permanent brackets had been installed at points about 10 feet upstream of each of the chosen stations. At each of those points the duct to be calibrated had been divided into squares about 2 feet across by means of wires attached to its walls, so as to define the positions at which the air-velocity was measured. The removable Pitot tube had then been calibrated with the air flowing through the duct at several velocities for each of the two fans provided. Any variation in the

fan speed during a test had been shown by a variation in the reading of the removable Pitot tube, and all such variations had been corrected for before working out the velocity coefficient of the removable Pitot tube for the particular measuring station. Having ascertained that the measuring station chosen was a suitable one, and having calibrated the removable Pitot tube with each of the two fans in operation, it was an easy matter at any subsequent date to install and adjust the impact-plate transmitter. Mr. Hodgson.

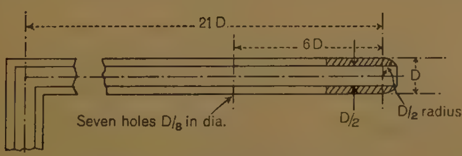
Fig. 17.



SUMMATION CIRCUIT.

Out of the fifteen measuring stations that had been so chosen, only one had proved to be unsuitable. In that case a permanent eddy, giving negative velocities, had formed on the one side of the duct. Also, the direction of the air-velocity in the tunnel itself had been found to affect the velocity at the chosen measuring point owing to the measuring point being too close to the exhaust-ceiling. As that particular duct branched higher up, measuring points in each of the branches were chosen, the potentiometers of the transmitters installed in the branches being connected in series as shown in *Fig. 17*.

Fig. 18.



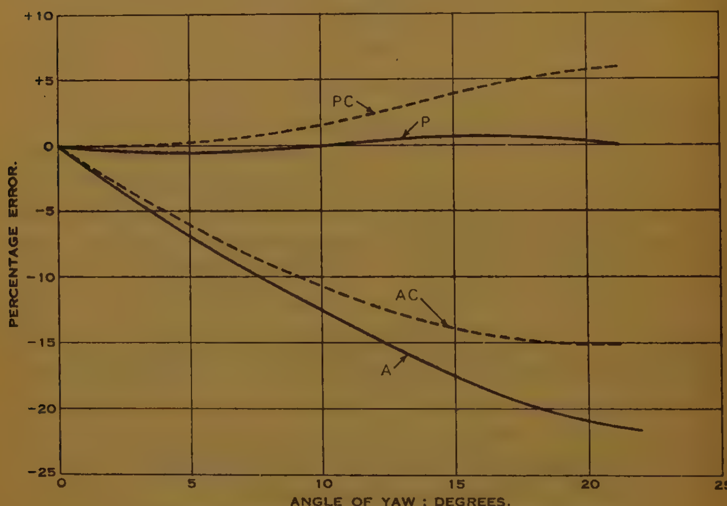
SPHERICAL-ENDED PITOT TUBE.

As the air-flow in the ducts was seldom parallel to their axes, the type of Pitot tube chosen (*Fig. 18*) was an adaptation of the spherical-ended Pitot tube described by Messrs. Ower and Johansen.[1] That type of Pitot tube had very small yaw-errors, and had been recommended by Mr. Hodgson for the original calibrations on which the size of the Mersey tunnel fans had been based. It had been found that when the readings of that Pitot tube were compared with those of certain anemometers commonly used in mining practice, very

[1] E. Ower and F. C. Johansen, "The Design of Pitot-Static Tubes," Technical Report of the Aeronautical Research Committee. R. & M. No. 981. H.M. Stationery Office, 1927.

Mr. Hodgson. considerable discrepancies occurred owing to those anemometers not being insensitive to yaw-error. To prove that it was the anemometers that were in error, he had had both the anemometers and the Pitot tube checked in a pulsating fan outlet, the intake air to the fan having been measured by means of a large plate-orifice for which the coefficient had been determined by his previous work. *Fig. 19* showed the results of those tests. Curves P and A showed the inaccuracies of the velocity measurement for the Pitot tube and the anemometer respectively when tested at various angles of yaw. Curves PC and AC showed those inaccuracies corrected for the cosine error, so that the measured velocity was resolved parallel to

Fig. 19.

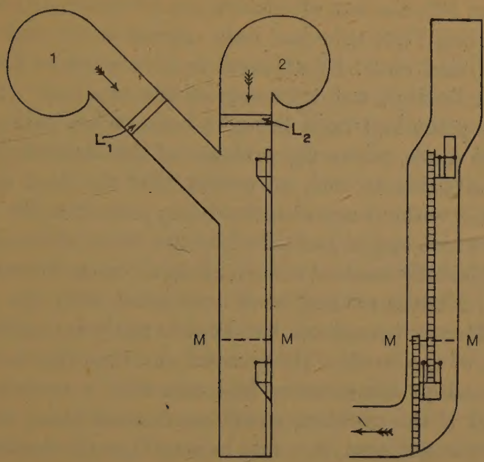


YAW-ERRORS FOR PITOT TUBES AND ANEMOMETERS.

the axis of the duct. Those curves indicated that even when the anemometer error was 10 per cent. (as was frequently the case), the spherical-ended Pitot-tube error would only be about 1·0 per cent. The matter was of considerable importance in connection with mine-air and fan measurements, as the anemometers tested had been of types approved and relied upon by mining experts. The reason why that large discrepancy between Pitot tube and anemometer readings had not previously been discovered was that anemometers were calibrated in wind-tunnels from which eddies and flow-irregularities had been carefully eliminated. The air-flow in the ducts had been frequently very gusty, variations of from 8 to 10 per cent. during 30 seconds in the velocity at a particular point being of common occurrence. Very often when the velocity rose at one point in the cros

Mr. Hodgson.

Figs. 20.

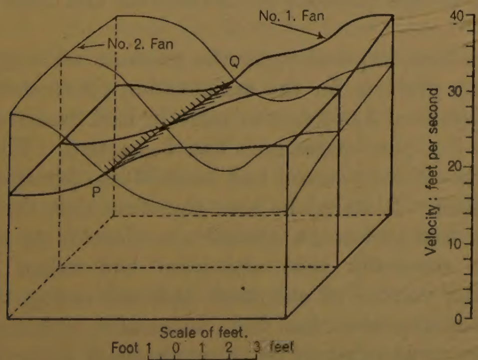


TAYLOR STREET BLOWING FANS AND DUCTS.

section of the duct, it fell at another. In spite of that gustiness, it was found that, by taking average readings over a period of time, very consistent results could be obtained, both when calibrating the standard Pitot positions, and when setting the impact-plate transmitters against the standard Pitot-tube readings.

A further difficulty which had had to be overcome had been that of using one transmitter at a measuring section such as MM (*Figs. 20*), where either of the fans 1 and 2 might blow through the louvres L_1 and L_2 respectively. He had overcome that difficulty by plotting velocity-distribution surfaces for the duct for the same total air-

Fig. 21.



AIR-VELOCITY CONTOURS OBTAINED AT MM IN *Figs. 20*

Mr. Hodgson. flows (*Fig. 21*), and then placing the impact-plate of the transmitter somewhere on PQ, the line of intersection of those surfaces.

The traversing Pitot tube had been carried at the end of a 12-foot bamboo pole, and could be adjusted so as always to face the flow. It could thus be kept well upstream of the observer. The importance of that point had been brought home when calibrating some of the smaller ducts, where the presence of the observer had affected the flow-distribution to such an extent that the final readings had had to be taken without any observer being present in the duct. The interference which might be caused by the body of an observer was often not sufficiently realized when making air-measurements in mines.

Mr. Neelands. Mr. A. R. Neelands had been associated with the preliminary work at the Mersey tunnel and had kept in fairly intimate touch with the progress of the work. He pointed out that the decision of the engineers to adopt cementation had met with a certain amount of criticism, but if the problem which confronted them at the outset were carefully considered, it would be seen that the decision had been justified. Certain information as to the amount of water pumped during the construction of the Mersey Railway had been available, and it had been known that 9,000 gallons per minute had been pumped from headings driven at a higher level than that of the proposed road-tunnel. Bunter Sandstone was notably capricious in its yield of water, and therefore at that time it had been practically impossible to assess what pumping capacity would be required to keep the workings dry. It had been known from the records of several shaft-sinkings that Red Sandstone could be successfully treated and from 85 to 95 per cent. of the water sealed, and cementation was therefore an insurance at a comparatively small cost (2·7 per cent. of the total cost) against possible delays and increased expenditure in all directions due to the difficulties of permanent construction in the presence of continuous and heavy feeders of water.

The restrictions imposed upon the pressure allowed had created an interesting problem for the cementation contractors. In shaft-sinking to depths of 1,000 feet or more in Red Sandstone, pressures up to 2,000 lbs. per square inch had been used. The permissible pressure at the Mersey tunnel had been 50 lbs. per square inch plus the static head. It would be seen therefore that the technique of cementation had had to be altered considerably to meet the new conditions. Generally that alteration had taken the form of increasing the volume of chemicals and decreasing the volume of cement; that expedient had been successful, although the results had not been so satisfactory as those obtained where there were no pressure restrictions.

Mr. Neelands.

It might be of some interest to assess the value of the process when operated with pressure restrictions. The total residual feeder from the shaft excavation, after cementation with no artificial pressure limits, had been found on 24 September, 1930, to be 32·5 gallons per minute. Information as to the quantities pumped during the excavation of the adjoining Mersey Railway shaft was not precise, but about 5,000 gallons per minute appeared to have been handled.

The total length of the drainage heading was approximately 1,500 feet. Partial cementation had been carried out after driving from chainage 300 feet to chainage 565 feet, and pre-cementation from chainage 736 feet to chainage 862 feet, a total of 265 feet plus 126 feet, or 391 feet. In those lengths the residual water had been weired where possible, and measurements giving a value of about 0·6 gallon per minute per foot-run had been obtained. The total residual flow from the heading had been 4,000 gallons per minute or 3·4 gallons per foot-run over the untreated parts. If the make of water over the drainage heading had been uniform after excavation the percentage which had been sealed by restricted cementation and silicatization was 77·5.

The Author gave a figure of 4,200 gallons per minute as the quantity pumped from the Liverpool shaft at one period. As the drainage heading feeder was 4,000 gallons per minute, the total from the tunnel and shaft excavation proper had been 200 gallons per minute, which did not appear an unduly large quantity when the size of the excavation was considered. The method appeared to have been justified by the results, and the Mersey tunnel operations certainly contributed to an improved knowledge of the possibilities of restricted-pressure cementation and silicatization in New Red Sandstone.

He thought that the conclusion of the last paragraph on p. 478 left some doubt as to the purpose of cementation and the reason for its discontinuance. He would like to make it clear that there had never been any suggestion that the cementation would render unnecessary the installation of a waterproof lining. The results expected from the cementation were: (1) that the quantity of water from the ground would be reduced to such an extent that the residual feeder would not affect the safety or the progress of the constructional operations, and (2) that the consolidation and strengthening of the rock, particularly in the roof, would give greater protection from any fall or from any inflow from the river. After the headings had progressed a certain distance from the river-bank the exploratory boreholes had indicated sound and dry rock; the necessity for cementation no longer arose and it had therefore been stopped. The exploratory drilling had continued in case there was any change in the

Mr. Neelands. strata, and the cementation plant had been retained in readiness to deal with any bad or wet ground that might have been encountered.

The figure of £153,000 given as the cost of cementation included the exploratory boring both in the treated and untreated ground, and the cube of ground treated included 1,000 yards of the excavated tunnel on a diameter of 46 feet 3 inches, plus a further 10 feet in radius minimum treatment to provide a protective surrounding.

The Author. The AUTHOR, in reply to various points raised at the Meeting and not dealt with at the time, and in reply to the Correspondence, stated that the explanation of the apparent contradiction between various speakers as to whether or not there was a longitudinal air-flow in the Holland tunnel might be that at times the flow would be affected by a strong wind blowing into the portals.

With regard to the air-velocity in the north and south air-ducts at the Mersey tunnel, the maximum speed was about 30 miles per hour, but at one time a speed of about 40 miles per hour had been considered when the supply of even greater quantities of fresh air had been contemplated. At a point half-way between George's Dock and the bulkhead at the mid-point under the river the speed was half that given above. Both "clean" and "dirty" mists had been experienced in the tunnel, but the mist was usually "dirty." The visibility-apparatus was sensitive to both types of mist. The apparatus had not been planned to actuate the tunnel lighting. The reasons why air-flow meters of the impact type had been chosen in preference to the Pitot tube type were given by the late Mr. Hodgson (p. 653). The impact type as installed was accurate to within $\pm 2{\cdot}5$ per cent. at minimum readings, which was quite sufficient for operating purposes.

With regard to the cementation process, the Author did not agree with the figures put forward by Mr. Neelands, but he quite agreed that it had never been suggested that the cementation process would render unnecessary the installation of a waterproof lining. The cementation process was useful and had been adopted for the reasons given, and it had been discontinued as soon as the engineers considered it advisable to do so.

He would point out that the references on pp. 496 and 497 to the Mount Victoria tunnel and Holland tunnel were incomplete. The statement with regard to the Mount Victoria tunnel should have read: "For the Mount Victoria tunnel in New Zealand, a formula was given which, when reduced to similar terms, . . ." The full reference to the formula given by Mr. Singstad was "Ole Singstad, "Ventilation of Vehicular Tunnels." World Engineering Conference, 1929, vol. ix, p. 381. Tokio, 1931.

NOTE: For Index, see end of Volume 3, 1935-36.